Sensing Performance of Dielectric Sensor in Mixed Melting Polymer Pellets for Waste Plastic Separation

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Abstract

Physical value of dielectric properties among relative permittivity, dielectric loss and loss tangent of mixed melting polymer pellets were measured under temperature variance condition and measurement frequency from 0.5 MHz to 5 MHz in order to develop a real-time non-intrusive measurement technique for high performance waste plastic separation. Various volume fractions of Non-polar polyethylene (PE) and polar polyethylene terephthalate (PET) were used as the mixed polymer pellets. As the results, with the volume fractions of PET from 0.05 to 0.22, as the temperature is increased up to melting point temperature and above mold temperature, the relative permittivity is decreased as the temperature is increased. However over melting temperature up to the mold temperature, the relative permittivity is slightly increased as the temperature is increased. On the other hand, the dielectric loss and loss tangent are not affected by the temperature variance, and the dielectric loss and loss tangent are increased as the measurement frequency is increased. As the conclusions, at molding temperature 180 °C (453 K), the highest sensitivity of dielectric property is the relative permittivity. Meanwhile, the highest linearity relationship between PET volume fraction and predicted relative permittivity is achieved at the measurement frequency of 5 MHz. From relative permittivity measurement in these conditions, the performance to distinguish PET volume fraction 0.05 from PE volume fraction 0.95 is achieved in the mixed melting polymer pellets. Therefore, the relative permittivity measurement for waste plastic separation has a possibility to achieve the high purity recycled plastics as compared with conventional methods.

Nomenclature

c	Capacitance	F
C_0	Cell constant	F
D	Distance of experimental setup	m
f	Measurement frequency	Hz
H	Height of experimental setup	m
k_B	Boltzmann constant	J/K
M	Molar mass	kg/mol
n	Data number	-
N_A	Avogadro constant	1/mol
P	Pressure	Pa
R	Radius of cylindrical electric furnace	m
T	Temperature	K
$\tan\delta$	Loss tangent	-
W	Width of experimental setup	m

Greek letters

α	Polarizability	C^2m^2/J
ε	Permittivity	F/m
ε''	Dielectric loss	-
ϕ	Volume fraction	-
κ	Conductivity	S/m
μ	Permanent dipole moment	Cm
ρ	Density of plastic	kg/m ³

Subscript

0	Vacuum
-deff	Difference value
a	Air
c	Cylindrical electric furnace
e	Electric
E	Electrode
g	Glass cell
i	i -th data number
l	Low value
m	Melt value
max	Maximum value
min	Minimum value
$mold$	Mold value
o	Atmosphere
p	Orientational value

<i>PE</i>	Polyethylene value
<i>PET</i>	Polyethylene terephthalate value
<i>r</i>	Relative value
<i>s</i>	Stray value
<i>v</i>	Vacuum container
Superscript	
<i>predicted</i>	Value from linear approximation
<i>real</i>	Value from experimental
-	Average

1. Introduction

Recycling waste plastics are highly paid attention for sustainable society. Waste plastics from home and office include basically 90 % major plastics such as polyethylene (PE), polystyrene (PS) and polypropylene (PP), and 10 % minor plastics such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC). A separation method from the mixed plastics is highly required to produce highly pure recycle plastic pellets. Conventional method is composed of two steps, which are a combination of an infrared separation method with air jet based on the refractive index difference value as first method, and a flotation separation method based on specific gravity difference value as second method. However, in the conventional method, the purity of recycled plastic pellets is usually less than 80%. Therefore, the operation by workers hands is needed to increase the purity. Especially, the separated PE includes anyhow different types of plastics such as less than around 10 % PET because of the separation performance limitation, resulting from the small difference in the refractive index and specific gravity between the mixtures. In order to achieve the high purity, third combination of separation method has been considered with integrating the in-line sensing of the mixture volume fraction as an extrusion process to produce recycle plastic pellets. The third combination separation method is needed a sensing technique to distinguish PET volume fraction in several kinds of mixed melting polymer pellets. However, the development is not already well established yet.

Generally, regarding in-line sensing for one type pure and virgin polymer, a dielectric sensor is often used to measure PE volume fraction of a granule flow by distinguish the relative permittivity distribution [1]. However, the dielectric sensor is strongly depended on temperature and measurement frequency. The characteristics of polymer dielectric properties such as relative permittivity, dielectric loss and loss tangent have been reported under molding temperature by a numerous researchers. Švorčík *et al.* obtained the relationship between relative permittivity and temperature for polymethyl methacrylate (PMMA) in composites to conclude that the relative permittivity is increased with temperature increase [2]. Neagu *et al.* measured a relative permittivity, dielectric loss and loss tangent with temperature and measurement frequency change for Nylon11; they concluded that the dielectric properties are increased

with temperature increase, and they are decreased with measurement frequency increase [3]. Coburn *et al.* obtained the relative permittivity and dielectric loss against temperature and measurement frequency for Polyethylene terephthalate (PET). The change of relative permittivity and dielectric loss have two peaks from 73 K (- 200 °C) to 413 K (140 °C). Also, the peak positions change due to the measurement frequency change [4]. In other words, the changes in dielectric properties depend on the polymer type, temperature and measurement frequency. However, the target temperatures of those dielectric properties from the scientific articles are extremely lower than melting temperature in an extruder for waste plastic separation. Therefore, from the engineering viewpoint, the dielectric properties of mixed melting polymer pellets are highly demanded to attain a high purity.

In this study, the optimal dielectric properties (i.e. relative permittivity, dielectric loss and loss tangent) of melting polymer pellets with various PET volume fractions are determined in order to indicate the detailed dielectric properties above melting temperature. Moreover, the optimal measurement frequency is determined under various conditions of temperature and measurement frequency in order to develop a best performance sensing technique to distinguish PET volume fraction in the mixture of non-polar polyethylene (PE) and polar polyethylene terephthalate (PET) for waste plastic separation.

2. Proposed sensing technique of mixed melting polymer for waste plastic separation

Figure 1 shows a proposed sensing technique of mixed melting polymer for waste plastic separation, which consists of a pulverizer, an infrared separation machine, a flotation separation machine, a drier, a deforming extruder, a sensing extruder, a dielectric sensor, a RC meter, a granulator, and a remover. The dielectric sensor is attached in a periphery of discharge pipe of the sensing extruder. At first, the recovered waste plastics are pulverized by a pulverizer. The pulverized waste plastics are separated by infrared separation method and flotation separation method. After the separations, the waste plastics are dried by a drier. The dried waste plastics are melted and fluidized in the deforming and the sensing extruders at molding temperature T_{mold} [K]. In the sensing extruder, the sensor measures PET volume fraction ϕ_{PET} [-] by physical value of dielectric properties, the low purity parts of melt polymer are removed by a remover with air jet after granulation. This third separation technique is assumed to contribute for producing highly pure recycled pellets. In this technique, three dielectric properties are selected, which are relative permittivity ϵ_r [-], dielectric loss ϵ'' [-] and loss tangent $\tan\delta$ [-]. The relationship between ϵ_r [-] and temperature T [K] in a polar polymer such as PET are expressed by Debye equation,

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{\rho N_A}{3\epsilon_0 M} (\alpha_e + \alpha_p) = \frac{\rho N_A}{3\epsilon_0 M} \left(\alpha_e + \frac{\mu^2}{3k_B T} \right) \quad (1)$$

where ϵ_0 is vacuum permittivity [F/m], M is molar mass [kg/mol], ρ is density [kg/m³], N_A is Avogadro constant = 6.02×10^{23} 1/mol, k_B is Boltzmann constant = 1.38×10^{-23} J/K, μ is permanent dipole moment [Cm], α_e is electric polarizability [C²m²/J], α_p is orientational polarizability [C²m²/J]. The trend of Debye equation indicates that ϵ_r is decreased as T is increased under ρ is constant [5]. In the case of non-polar polymer such as PE, α_p term is deleted because μ is zero; namely, Clausius-Mosotti equation is expressed by

$$\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{\rho}{M} \frac{N_A}{3\epsilon_0} \alpha_e \quad (2)$$

From this equation, ϵ_r is decreased as ρ is decreased [6].

Meanwhile, ϵ'' is expressed by

$$\epsilon'' = \frac{\kappa}{2\pi f \epsilon_0} \quad (3)$$

κ is conductivity [S/m] which depends on T , and f is measurement frequency [Hz]. From this equation, ϵ'' depends on T and f .

$\tan \delta$ is the ratio of ϵ_r and ϵ'' as [5]. And also depend on T and f ;

$$\tan \delta = \frac{\epsilon''}{\epsilon_r} \quad (4)$$

Fig. 1 The Proposed Sensing technique of mixed melting polymers

3. Experiments

3.1 Experimental setup

Figure 2 (a) shows the overall schematic diagram of experimental setup which was composed of an electric furnace (Model MCK11-1010, Motoyama Co.Ltd Japan), a petri dish, a multi controller (Model FKC-12, TKG Japan), two glass cells, an impedance analyzer (Model IM3570, Hioki E.E. Corporation Japan), a four-terminal probe (L2000, Hioki E.E. Corporation Japan), three thermocouples (Model KTO-16200 type K, As One Corporation Japan), a data logger/switching unit (Model 34970A, Agilent technologies company USA) and a vacuum container. The atmosphere in cylindrical electric furnace with the radius $R = 50$ mm and the height $H_c = 150$ mm was heated up homogeneously by heating wires located in the side wall. The petri dish was located at top of the electric furnace for temperature stabilization. The multi controller was regulated the inside temperature for each 1.00 K (1.00 °C) by means of proportional integral derivative control. Figure 2 (b) shows the glass cells, electrodes, K-type thermocouples, coaxial cables, and

crocodile clips inside the electric furnace. Both glass cells which were a capacitance measurement cell and a temperature measurement cell were made of a quartz glass with $D_g \times H_g \times W = 10.0 \text{ mm} \times 50.0 \text{ mm} \times 50.0 \text{ mm}$, and had two copper electrodes with $H_E \times W = 10.0 \text{ mm} \times 50.0 \text{ mm}$ inside the larger wall. The impedance analyzer measured the impedance and phase angle with various measurement frequencies f . The end of four terminals probe from the impedance analyzer was clipped by using crocodile clips at the top of the copper electrodes in the glass cell. One thermocouple was located in the other glass cell, and the other thermocouple was located at the atmosphere. Both thermocouples were connected to the data logger/switching unit to record the temperature T . The vacuum container consists of a pressure gauge, a vacuum valve, a leak valve, a vacuum pump and a brick. The vacuum container with the height $H_v = 545 \text{ mm}$, the width $W_v = 390 \text{ mm}$, the internal depth $D_v = 446 \text{ mm}$ was used for sample preparation as explained in 3.2 section in order to avoid bubble inclusions during the measurement. The vacuum valve was connected to a vacuum pump and the leak valve was used for atmospheric release. The furnace was located on the bricks for thermal insulation.

(a) Overall schematic diagram

(b) Inside electric furnace

Fig. 2 Experimental setup

3.2 Sample Preparation Procedure

Figure 3 shows the polyethylene (PE) and polyethylene terephthalate (PET) pellets, which are elliptic cylinder shape. Table 1 shows two kinds of polymer pellet properties which are non-polar PE (LJ902, Japan polyethylene Corporation) and polar PET (TRN-8380AC, Teijin limited Japan). Polar plastics have permanent dipole moment μ , which is represent the deviation of positive and negative charge of the molecule in the absence of an electric field. Based on this fact, permittivity of polar plastics is larger than nonpolar plastics [7]. Also, the molding temperature T_{mold} must be more than the melting temperature T_m and less than the deterioration temperature. The pellet size indicates the value of the longest diameter, the shortest diameter, and height. The $\pm$ value in parenthesis is deviation. Table 2 shows four samples with various combination of each PET volume fraction ϕ_{PET} around 10 % from the viewpoints of real separation situation. As a reference, Sample 4 is only PET, which has the maximum $\phi_{PET} = 1.00$.

At first in the procedure, the pellets as shown in Fig. 3 were put into both glass cells in the electric furnace. The furnace was covered with the petri dish, and the vacuum container was closed. The vacuum pump was operated from atmospheric pressure $P_0 = 0.00$ MPa Gauge to low pressure $P_l = -0.09$ MPa Gauge. The maximum temperature inside the furnace was set as 473 K (200 °C) for Samples 1 to 3 and 523 K (250 °C) for Sample 4 to be held for 40 minutes to achieve a constant temperature for each sample. According to the thermal diffusion differential equation, the 40 minutes are confirmed to be steady and uniform temperature condition. After 40 minutes of holding, the vacuum valve was closed and the leak valve was opened. The pressure inside the vacuum container was naturally reached to P_0 . After reaching P_0 , the furnace and the pump were turned off. Thus, the temperature was decreased down to room temperature; the mixed samples without any bubbles were obtained. All sample volumes were 6,000 mm³.

Fig. 3 PE and PET pellets

Table 1 Polymer properties of and experiment condition [7] [8]

	PE	PET
Chemical formula	$-(C_2H_4)_n-$	$-(C_{10}H_{10}O_4)_n-$
Polarity	Non-polarity	Polarity
Crystalline/Amorphous	Crystalline	Crystalline
Melting temperature T_m [K]	375	498
Molding temperature T_{mold} [K]	453	543
Pellet size ($\pm$ deviation)	$3.98 (\pm 0.0908) \times 2.67 (\pm 0.110) \times 3.11 (\pm 0.169)$ mm	$2.98 (\pm 0.102) \times 2.59 (\pm 0.228) \times 3.08 (\pm 0.279)$ mm

Table 2 PET volume fraction of 4 samples

	PET volume fraction of PE $1-\phi_{PET}$ [-]	PET volume fraction ϕ_{PET} [-]
Sample 1	0.95	0.05
Sample 2	0.90	0.10
Sample 3	0.78	0.22

Sample 4	0.00	1.00
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3.3 Experimental Conditions and Methods

The experimental maximum temperature T_{max} were 473 K (200 °C) for Samples 1 to 3 and 523 K (250 °C) for Sample 4 after the sample preparation procedure. The polymer T_{max} was set above PE molding temperature $T_{mold-PE} = 453$ K (180 °C) for PE, and then the temperature was held for 40 minutes in T_{max} . After that, the electric furnace was turned off to start the measurements during the natural cooling until approximate $T_{min} = 253$ K (30 °C). During the natural cooling, the impedance analyzer measured the capacitance c and loss tangent $\tan\delta$ with various measurement frequencies f from 0.5 MHz to 5 MHz after open/short compensation. The measurement values were averaged by each 10 K (10 °C) decrement. Calibration of c is necessary because the stray capacitance c_s occurs from the electrodes shapes and the cables. c_s can be described by

$$c_s = c_a - \varepsilon_a C_0 \quad (5)$$

where c_a is the air capacitance and C_0 is the cell constant [9], and ε_a is the air relative permittivity, which is equal to 1.00. Meanwhile, C_0 is described by

$$C_0 = \varepsilon_0 \frac{H_E \times W}{D_g} \quad (6)$$

where $H_E \times W$ is the electrode area and D_g is the distance between electrodes. In order to remove c_s , the polymers relative permittivity ε_r is calibrated by

$$\varepsilon_r = \frac{c - c_s}{C_0} \quad (7)$$

This calibration is performed in each temperature T because c_s is dependent on each T . The data logger/switching unit measured T synchronizedly at the same time as the impedance analyzer measurement.

4. Experimental results

4.1 Relative Permittivity in Mixed PE and PET

Figures 4 (a) and (b) show the relationship between temperature T and relative permittivity ε_r as a parameter of measurement frequency $f = 0.5$ MHz, 1 MHz, 2 MHz, 3 MHz, 4 MHz and 5 MHz in the case of Sample 1 ($\phi_{PET} = 0.05$), Sample 2 ($\phi_{PET} = 0.10$), Sample 3 ($\phi_{PET} = 0.22$), and Sample 4 ($\phi_{PET} = 1.00$), respectively. From the results of Sample 1 to 3, basically, ε_r is dependent on T ; ε_r is decreased as T is increased up to around PE melting temperature T_{m-PE} because the polymer volume is expanded, the polymer

density ρ is decreased based on Eq.(2). Above T_{m-PE} up to PE mold temperature $T_{mold-PE}$, ϵ_r is slightly increased as T is increased. Above $T_{mold-PE}$, ϵ_r is slightly decreased as T is increased. In the case of Sample 4 ($\phi_{PET} = 1.00$), ϵ_r curve indicates a peak at $T = 423$ K (150 °C). In polar polymer, the effect of orientation polarization α_p is dominant, and several relaxations are shown in wide temperature region. The corresponding temperature of each relaxation is almost constant irrespective of f . Namely, the temperature dependence of ϵ_r in PET is more complex than that in PE. Table 3 shows ϵ_r gradient of Samples 1 to 3 up to T_{m-PE} . According to Table 3, the gradient is decreased as ϕ_{PET} is increased. On the other hand, in the polar polymer, the permanent dipole moment μ represents the deviation of positive and negative charge of the molecules constituting the polymer without an electric field. A large number of dipole lower temperature zone can easily orient in the external electric field direction because ϵ_r at T is increased. That proceeds polarization because dipoles is easy to move, ϵ_r tends to increase with T increase. However, ϵ_r is tend to decrease with increasing T over the order-disorder transition temperature which is one of the phase transition temperature. This is caused by a thermal disturbance of the dipole orientation and further density decrease [5].

(a) $\phi_{PET} = 0.05$ and $\phi_{PET} = 0.10$

(b) $\phi_{PET} = 0.22$ and $\phi_{PET} = 1.00$

Fig. 4 Temperature dependence of relative permittivity ϵ_r

Table 3 Line gradient below T_{m-PE} in $f = 5$ MHz

	gradient $\times 10^{-3}$ [1/K]
Sample 1	-3.64
Sample 2	-2.89
Sample 3	-1.50

4.2 Dielectric Loss in Mixed PE and PET

Figures 5 (a) and (b) show the relationship between temperature T and dielectric loss ϵ'' as a parameter of measurement frequency $f = 0.5$ MHz, 1 MHz, 2 MHz, 3 MHz, 4 MHz and 5 MHz in the case of Sample 1 (PET volume fraction $\phi_{PET} = 0.05$), Sample 2 ($\phi_{PET} =$

0.10), Sample 3 ($\phi_{PET} = 0.22$), and Sample 4 ($\phi_{PET} = 1.00$), respectively. From mixed sample (Sample 1 to 3) results, ε'' are almost constant regardless of T . As ϕ_{PET} and f are increased, the variation and value of ε'' become larger. In the case of Sample 4, the peak value of ε'' to T is shown as a dot-and-dash line, and the peak position tends to move to higher temperature as f is increased. The peaks exhibit the correspondence to primary relaxation. In terms of the polar polymers, ε'' shows a graph of a mountain-shaped having the maximum value at the position where relative permittivity ε_r peaks at the order-disorder transition temperature. On the other hand, in the non-polar polymer indicates only ionic polarization and electronic polarization. For this reason, ε'' change of Samples 1 to 3 is smaller than the Sample 4 change.

(a) $\phi_{PET} = 0.05$ and $\phi_{PET} = 0.10$

(b) $\phi_{PET} = 0.22$ and $\phi_{PET} = 1.00$

Fig. 5 Temperature dependence of dielectric loss ε''

4.3 Tangent Delta in Mixed PE and PET

Figures 6 (a) and (b) show the relationship between temperature T and loss tangent $\tan\delta$ as a parameter of measurement frequency $f = 0.5$ MHz, 1 MHz, 2 MHz, 3 MHz, 4 MHz and 5 MHz in the case of Sample 1 (PET volume fraction $\phi_{PET} = 0.05$), Sample 2 ($\phi_{PET} = 0.10$) and Sample 3 ($\phi_{PET} = 0.22$), and Sample 4 ($\phi_{PET} = 1.00$), respectively. From Sample 1 to Sample 3 results, $\tan\delta$ is almost constant irrespective of T . As ϕ_{PET} and f are increased, the variation and value of $\tan\delta$ become larger. In the case of polar plastics (Sample 4), the peak value of $\tan\delta$ in terms of T is shown as a dot-and-dash line, and the peak position tends to move to higher temperature as f is increased. The peaks exhibit the correspondence to primary relaxation. Also, the amount of $\tan\delta$ peak movement against T is smaller than the amount of ε'' .

(a) $\phi_{PET} = 0.05$ and $\phi_{PET} = 0.10$

(b) $\phi_{PET} = 0.22$ and $\phi_{PET} = 1.00$

Fig. 6 Temperature dependence of loss tangent $\tan\delta$

5. Discussion

5.1 Optimal dielectric properties in mixed melting polymer pellets

The optimal physical value of dielectric properties among relative permittivity ϵ_r , dielectric loss ϵ'' and loss tangent $\tan\delta$ should be selected in mixed melting polymer pellets to achieve the best performance for waste plastic separation from the viewpoint of high sensitivity and linearity. Figure 7 and 8 show the relationship between PET volume fraction ϕ_{PET} and ϵ_r at PE molding temperature $T_{mold-PE} = 453$ K (180 °C), the relationship between ϕ_{PET} and ϵ'' at $T_{mold-PE}$, and the relationship between ϕ_{PET} and $\tan\delta$ at $T_{mold-PE}$. From these figures, ϵ_r is linearly increased as ϕ_{PET} is increased; however, ϵ'' and $\tan\delta$ are not linearly increased. Concretely, ϵ'' and $\tan\delta$ is increased rapidly from $\phi_{PET} = 0.10$ to $\phi_{PET} = 0.22$. Also, different values between the dielectric properties at $\phi_{PET} = 0.05$ and the dielectric properties at $\phi_{PET} = 0.1$ must be required in this proposed method because the conventional separation method cannot achieve less than 10 % PET sensing. Figure 9 shows the relationship between the difference values of $|\epsilon_{r-diff}|$, $|\epsilon''_{-diff}|$ and $|\tan\delta_{-diff}|$ versus f at $T_{mold-PE}$. $|\epsilon_{r-diff}|$ indicates the different value between ϵ_r ($\phi_{PET} = 0.10$) and ϵ_r ($\phi_{PET} = 0.05$). The $|\epsilon''_{-diff}|$ indicates the different value between ϵ'' ($\phi_{PET} = 0.10$) and ϵ'' ($\phi_{PET} = 0.05$). The $|\tan\delta_{-diff}|$ indicates the different value between $\tan\delta$ ($\phi_{PET} = 0.10$) and $\tan\delta$ ($\phi_{PET} = 0.05$). Among the difference values, $|\epsilon_{r-diff}|$ is the largest among $|\epsilon_{r-diff}|$, $|\epsilon''_{-diff}|$ and $|\tan\delta_{-diff}|$ regardless of f . From the viewpoint of high sensitivity, ϵ_r is most appropriately chosen among three dielectric properties in mixed melting polymer pellets in order to achieve the best performance.

Table 4 shows the linear approximation with a slope A and an intercept B between ϕ_{PET} and ϵ_r as a parameter of f . From the viewpoint of high linearity, $f = 5$ MHz is the optimal condition because of the largest gradient of the linear approximation.

Fig. 7 Relative permittivity ϵ_r and dielectric loss ϵ'' versus ϕ_{PET} in various f at $T_{mold-PE}$

Fig. 8 Relative permittivity ϵ_r and loss tangent $\tan\delta$ versus ϕ_{PET} in various f

Fig. 9 Difference of dielectric properties $|\varepsilon_{r-diff}|$, $|\varepsilon''_{-diff}|$ and $|\tan\delta_{-diff}|$ between $\phi_{PET} = 0.1$ and $\phi_{PET} = 0.05$ against f

Table 4 Liner approximation between ϕ_{PET} and ε_r

$T_{mold-PE} = 453 \text{ K (180 } ^\circ\text{C)}$	A	B
0.5 MHz	3.39	1.91
1 MHz	3.39	1.92
2 MHz	3.39	1.93
3 MHz	3.41	1.98
4 MHz	3.43	2.03
5 MHz	3.48	2.08

5.2 Sensing performance in mixed melting polymer pellets

According to the discussion of 5.1 section, in terms of the high sensitivity and the linearity, the relative permittivity ε_r with measurement frequency $f = 5 \text{ MHz}$ is the best physical value among dielectric properties to detect PET volume fraction ϕ_{PET} in waste plastic separation process. However, the best physical value is necessary to examine the measurement standard deviation σ from the atmosphere and the measurement system and the difference between real ϕ_{PET} and linear approximation in Table 4. Also, the optimal f condition is discussed at the fixed **PE** molding temperature $T_{mold-PE} = 453 \text{ K (180 } ^\circ\text{C)}$ to recognize how much minimum ϕ_{PET} is in mixed melting polymer pellets. First, σ of ε_r at each f and various ϕ_{PET} at the fixed room temperature is

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{i=n} (\bar{\varepsilon}_r - \varepsilon_{ri})^2} \quad (8)$$

where n is the data number, ε_{ri} is the relative permittivity of i -th data number, and $\bar{\varepsilon}_r$ is the 100 times average of measured ε_r . Figure 10 shows the relationship between f and σ in various ϕ_{PET} . From this figure, $f = 0.5 \text{ MHz}$ has the smallest σ value.

Furthermore, the accuracy order of predicted PET volume fraction $\phi_{PET}^{predicted}$ is analyzed based on σ . $\phi_{PET}^{predicted}$ is defined from the value which is calculated from the linear approximation as showed in Table 4 and the i -th measured ε_{ri} . In the case of normal probability distribution, when the i -th measured ε_{ri} is under 95.45 %, the probability has a range of

$$\varepsilon_r - 2\sigma \leq \varepsilon_{ri} \leq \varepsilon_r + 2\sigma \quad (9)$$

Because of

$$\phi_{PET}^{predicted} = \frac{\varepsilon_r - B}{A} \quad (10)$$

$\phi_{PET}^{predicted}$ has a range of

$$\frac{\varepsilon_r - 2\sigma - B}{A} \leq \phi_{PET}^{predicted} \leq \frac{\varepsilon_r + 2\sigma - B}{A} \quad (11)$$

Therefore, the difference between $\phi_{PET}^{predicted}$ and ϕ_{PET}^{real}

$$\frac{\phi_{PET}^{real} - \frac{\varepsilon_r - 2\sigma - B}{A}}{\phi_{PET}^{real}} \times 100 \leq \frac{\phi_{PET}^{real} - \phi_{PET}^{predicted}}{\phi_{PET}^{real}} \times 100 \leq \frac{\phi_{PET}^{real} - \frac{\varepsilon_r + 2\sigma - B}{A}}{\phi_{PET}^{real}} \times 100 \quad (12)$$

Figure 11 shows the relationship between f and the difference value which is dependent on f . The optimal f showing the smallest difference value is $f = 5$ MHz. The difference values in $f = 5$ MHz in the case of $\phi_{PET}^{real} = 0.05, 0.1, 0.22$ and 1.0 are 25.1, 4.68, 9.41 and 0.346 %, respectively. Therefore, this study proposes a new high performance sensing technique of mixed melting polymer pellets to distinguish $\phi_{PET}^{real} = 0.05$ from the PE volume fraction 0.95 by using ε_r with optimal $f = 5$ MHz.

Fig. 10 Standard deviation of relative permittivity against measurement frequency in various ϕ_{PET}

Fig. 11 Relationship between f and difference value from ϕ_{PET}^{real} to $\phi_{PET}^{predicted}$

6. CONCLUSIONS

Physical values of dielectric properties among relative permittivity ε_r , dielectric loss ε'' and loss tangent $\tan\delta$ in melting mixture of PE and PET were measured in various measurement frequency f from 0.5MHz to 5MHz in order to indicate the dielectric properties above melting temperature and to develop a new high performance sensing technique for waste plastic separation. The conclusions are obtained as follows.

- 1) In PET volume fraction from $\phi_{PET} = 0.05$ to $\phi_{PET} = 0.22$, ε_r is decreased as T is increased up to around PE melting temperature T_{m-PE} .

Over T_{m-PE} up to PE mold temperature $T_{mold-PE}$, ε_r is slightly increased as T is increased. Over $T_{mold-PE}$, ε_r is slightly decreased as T is increased. ε'' and $\tan\delta$ are almost constant irrespective of T . As ϕ_{PET} and f are increased, the variation and value of ε'' and $\tan\delta$

becomes larger. In the case of $\phi_{PET} = 1.00$, ε_r curve indicates a peak at $T = 423$ K (150 °C). The peak positions of ε'' and $\tan\delta$ move to higher temperature as f is increased. Also, the movement amount of $\tan\delta$ peak against T is smaller than the movement amount of ε'' .

- 2) From the viewpoint of high sensitivity, ε_r is the best physical value among the three dielectric properties in mixed melting polymer pellets to achieve the best performance. From the viewpoint of high linearity, $f = 5$ MHz is the optimal condition because of the largest gradient of the linear approximation at the molding temperature $T_{mold-PE} = 180$ °C.
- 3) The difference values between real PET volume fraction ϕ_{PET}^{real} and predicted PET volume fraction $\phi_{PET}^{predicted}$ in $f = 5$ MHz in the case of $\phi_{PET}^{real} = 0.05, 0.1, 0.22$ and 1.0 are 25.1, 4.68, 9.41 and 0.346 %, respectively. This study proposes a new high performance sensing technique of mixed melting polymer pellets to distinguish $\phi_{PET}^{real} = 0.05$ from the PE volume fraction 0.95 by using ε_r with optimal $f = 5$ MHz.

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Figure1

Figure2 (a)

Figure2 (b)

Figure3

Figure4 (a)

Figure4 (b)

Figure5 (a)

Figure5 (b)

Figure6 (a)

Figure6 (b)

Figure7

Figure8

Figure9

Figure10

Figure11

Proposed sensing technique for high performance waste plastic separation by using dielectric sensor

*The **highest sensitivity** and **linearity** are ϵ_r and $f = 5\text{MHz}$ in PE mold temperature.

*The performance to distinguish 0.05 PET volume fraction to 0.95 volume fraction of PE is achieved in the mixed melting polymer pellets.