An Investigation on Thermal Recycling of Recycled Plastic Resin (Effects of Replacement Rate and Median Diameter of PET-Resin Powder on In-Furnace Combustion)*

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Abstract
To examine the possibility of thermal recycling of waste PET bottles, a commercial LPG-fueled ceramic burner has been first improved to burn PET-resin powder as an auxiliary fuel and the combustion characteristics have been investigated by varying the median diameter and the mass flow rate of PET-powder. According to the results, the proposed burner realized reasonable combustion performance comparable to the original LPG-fueled ceramic burner, being reliable experimental certification to the possibility and availability of the proposed idea. The use of PET-resin powder as one of the alternative fuels in the ceramic kiln furnace was also found to be efficient from the viewpoint of saving energy resources and attaining low environmental impact. In this paper, under the fixed conditions of a total heat input of 11.6 kW and an overall equivalence ratio of 0.8, the combustion characteristics of the improved burner are experimentally investigated in the model furnace by varying the replacement rate and the mass median diameter of PET-powder. Brief qualitative discussion on the behavior of unburnt PET particles is also made by transforming the mass-based histograms to the profiles of particle number fraction of virtual spherical particles.

Key words: Heterogeneous Combustion, Thermal Recycling, PET-Resin Powder, Ceramic Kiln Furnace, Replacement Rate, Reduced Circumstances

1. Introduction

Recent remarkable production of plastic resin promotes wide and abrupt use of plastic resin products, such as polyethylene terephthalate bottles (abbreviated to PET bottles in the following), plastic bags and plastic films, because of their cheapness, lightness, flexibility and cleanliness. Extreme increase in waste matters of plastic resin, however, requires new and effective techniques for reusing and/or processing them. In this investigation, taking account of the fact that waste PET-resin is one of the oxygenated hydrocarbon fuels having high purity and has a lower heating value of 21.8 MJ/kg, being comparable to pulverized coal, reuse of recycled PET-resin powder as an auxiliary or additional fuel is attempted, since it realizes simultaneously thermal recycling of PET-resin and saving fossil energy resources.
In the preceding investigations (1)-(3), a commercial LPG-fueled ceramic burner has been improved first so that direct introduction of fusible PET-powder into the main combustion zone of the burner and prevention of dissolved PET-resin from adhering the burner wall can be simultaneously realized. Combustion characteristics have then been examined in the in-furnace operation of the improved burner for two extreme conditions without and with PET-powder supply. It has been found that the possibility of thermal recycling of waste PET-resin as an auxiliary fuel can be clearly demonstrated based on flexibility not only to retro-fit the improved burner to the established industrial burner system, but also to adjust in-furnace circumstances either oxidizing or reducing. Further examinations of burning behavior and exhaust gas properties in the in-furnace operation should be made, since they are influenced greatly by the replacement rate and the median diameter of PET-powder.

In this paper effects of the latter two factors on the in-furnace combustion characteristics are first examined and, in connection with the PET-powder median diameter, the maximum replacement rate is estimated under a constant total heat input of 11.6 kW into the improved burner. Uniformity of the spatial temperature field is then certified, when the replacement rate is set to the maximum value of 30 %. A sintering test is also made using some specimens under two extreme conditions without and with PET-powder supply at the replacement rate of 15 %. Based on the results concerning the whiteness and 3-point bending strength, the validity of PET-powder as an alternative fuel in the ceramic industries is indicated.

2. Nomenclature

\[ d \] : diameter of PET particle \[ \mu m \]

\[ d_{\text{mm}} \] : median diameter of PET-powder \[ \mu m \]

\[ \Delta H_{\text{PET}} \] : lower heating value of PET-resin \[ MJ/kg \]

\[ \Delta H_{\text{C3H8}} \] : lower heating value of propane \[ MJ/m^3 \]

\[ H_{\text{PET}} \] : heat release rate of PET-powder \[ kW \]

\[ H_t \] : total heat release rate \[ kW \]

\[ Q_{\text{a,m}} \] : main air flow rate for propane \[ L/min \]

\[ Q_{\text{f,m}} \] : propane flow rate \[ L/min \]

\[ Q_{\text{a,PET}} \] : air flow rate for PET-powder conveyance \[ L/min \]

\[ Q_{\text{a,t}} \] : total air flow rate \[ Q_{\text{a,m}} + Q_{\text{a,PET}} \] \[ L/min \]

\[ q_0 \] : particle number fraction, defined by Eq. (3) \[%\]

\[ q_3 \] : particle mass fraction \[%\]

\[ m_i \] : particle mass in the \( i \)-th step per unit mass of PET-powder \[ kg \]

\[ m_{\text{PET}} \] : mass flow rate of PET-powder \[ g/min \]

\[ N \] : total particle number of virtual PET-powder \[-\]

\[ n_i \] : virtual particle number in the \( i \)-th step \[-\]

\[ T \] : temperature in the furnace \[ ^\circ C \]

\[ T_{\text{ex}} \] : exhaust gas temperature \[ ^\circ C \]

\[ T_s \] : spatial average temperature in the furnace \[ ^\circ C \]

\[ X_i \] : virtual particle diameter in the \( i \)-th step \[ \mu m \]

\[ \alpha \] : replacement rate of PET-powder (= auxiliary burning rate), defined by Eq. (2) \[%\]

\[ \phi \] : overall equivalence ratio, defined by Eq. (1) \[-\]

\[ \rho_{\text{PET}} \] : density of PET-resin \[ kg/m^3 \]

3. Experimental Apparatus and Methods

3.1 Schematic Diagram of Experimental Apparatus

The schematic diagram of the experimental apparatus used in this investigation (1), which is not given in this paper, consists of an improved ceramic burner, a main air supply
line, a fuel supply line, a PET-powder supply line, a model furnace, and a set of measuring instruments. Commercial LPG having a propane purity of 96.4 % and a lower heating value of $\Delta H_{\text{C3H8}} = 83.8 \text{ MJ/m}^3$ is used as a main fuel, whereas PET-powder is employed as an auxiliary fuel.

### 3.2 Properties of PET-Powder

PET-powder has a lower heating value of $\Delta H_{\text{PET}} = 21.8 \text{ MJ/kg}$ and a density of $\rho_{\text{PET}} = 1.38 \times 10^3 \text{ kg/m}^3$. In Fig. 1, examples of micrographs and mass-based histograms are presented for three kinds of PET-powder having a median diameter of (a) $d_m = 89.7 \mu\text{m}$, (b) $d_m = 145 \mu\text{m}$ and (c) $d_m = 185 \mu\text{m}$. The ordinate in the histogram means the particle mass fraction $q_3 [%]$ in each size step. Micrographs clarify first that PET-powder is generally composed of particles having various sizes and shapes and exhibits uneven and ragged appearances, and that the larger the median diameter $d_m$ becomes, the greater the number of large and coarse particles becomes. Histograms in Fig. 1 indicate, on the other hand, that the particle size distributes widely in the range of (a) 25 ~ 380 $\mu\text{m}$ for the PET-powder of $d_m = 89.7 \mu\text{m}$, (b) 30 ~ 440 $\mu\text{m}$ for $d_m = 145 \mu\text{m}$ and (d) 43 ~ 680 $\mu\text{m}$ for $d_m = 185 \mu\text{m}$.

### 3.3 Construction and Dimensions of the Model Furnace

In Fig. 2, construction and dimensions of the rectangular model furnace used in this investigation are shown. It has inner dimensions of 400 mm height, 400 mm depth and 700 mm length, giving an inner volume of 0.112 m$^3$, and is constructed using commercial ceramic fiber boards with a thickness of 100 mm and a heat-resisting temperature of 1400 °C.

As shown in Fig. 2, the improved burner is set at the center of the third quadrant of the front side wall having a square section of 400 mm $\times$ 400 mm, by considering the convection

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$Q_{\text{e.m}}$ L/min</th>
<th>$Q_{\text{a.m}}$ L/min</th>
<th>$Q_{\text{a.PET}}$ L/min</th>
<th>$m_{\text{PET}}$ g/min</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>8.3</td>
<td>233</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>7.9</td>
<td>232</td>
<td>11.7</td>
<td>1.6</td>
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<tr>
<td>15</td>
<td>7.0</td>
<td>229</td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td>30</td>
<td>5.8</td>
<td>222</td>
<td>14.7</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Table 1 Experimental conditions ($H_t = 11.6 \text{ kW}, \phi = 0.8$)
pattern of high speed combustion gas flow in the model furnace. The exit section of improved burner is set flush to the inner wall of the model furnace. An exhaust duct having an inner diameter of 100 mm and a length of 280 mm is coaxially settled with the exhaust gas port of 28 mm diameter at the central position of the upper wall, as shown in Fig. 3.

3.4 Definitions of Overall Equivalence Ratio and Replacement Rate

Two kinds of fuels, commercial LPG and PET-powder, are used in this investigation. The overall equivalence ratio $\phi$ is defined by the following expression, based on the propane flow rate $Q_{f,m}$, the PET-powder mass flow rate $m_{PET}$, and the total air flow rate $Q_{a,t}$, where the latter is given by the sum of the main air flow rate for propane $Q_{a,m}$ and the auxiliary air flow rate for PET-powder $Q_{a,PET}$ as $Q_{a,t} = Q_{a,m} + Q_{a,PET}$.

$$\phi = \frac{23.8 \times Q_{f,m} + 5.56 \times m_{PET}}{Q_{a,m} + Q_{a,PET}}$$  \hspace{1cm} (1)

In Eq. (1), the theoretical air amount of PET-powder is evaluated by assuming a chemical formula as $(C_{10}H_{8}O_{4})_n$.

The replacement rate of PET-powder $\alpha$, on the other hand, is defined by the ratio of the heat release rate of PET-powder $H_{PET}$ to the total heat release rate $H_t$, being equivalent to the assist burning rate.

$$\alpha = \frac{H_{PET}}{H_t} = \frac{H_{PET} \times m_{PET}}{(\Delta H_{CH_3}) \times Q_{f,m} + \Delta H_{PET} \times m_{PET}}$$  \hspace{1cm} (2)

In Table 1, four sets of the flow conditions and the PET-powder mass flow rates for the replacement rate of $\alpha = 0$, 5, 15 and 30 % are summarized under a constant total heat release rate of $H_t = 11.6$ kW and a constant overall equivalence ratio of $\phi = 0.8$.

3.5 Examination of Whiteness and Bending Strength of Glazed Test Species

Comparison of the whiteness and bending strength of glazed test species are made after an hour operation in the two extreme cases without and with PET-powder supply. The replacement rate of PET-powder is kept constant at $\alpha = 15 \%$. Measurements of the whiteness of test species are made using Three-Dimensional Spectroscopic Polarized Color Meter (Nippon Densyoku Kogyo, GC-Σ90). Three-point bending tests, on the other hand, are made using Universal Compression and Tensile Testing Machine (Yonekura Seisakusyo, CATY-200 BL), in which a moving velocity of cross-head is set to 0.5 mm/s and a distance between two fulcrums is set to 50 mm, following the standard for 3-point bending test of tableware ceramics (Standard of Japan Ceramics Institute, JCRS203-1996). Each property is estimated using each numerical value averaged over six data for each sintering condition.

3.6 Experimental Procedure and Methods

Based on the total heat release rate and the overall equivalence ratio, the flow rates of
propane, main air for propane combustion and auxiliary air for PET-powder conveyance are first prescribed and supplied to the improved burner to establish the main propane-air flame. For realizing a long residence time in high temperature atmosphere and enabling efficient burn-out of PET-powder, a series of physical processes from solid heating to thermal decomposition should be promoted fluid-dynamically. To accomplish the requirement, the minimum auxiliary air flow rate is assigned to \( Q_{a,PET} = 11.7 \text{ L/min} \) for the replacement rate of \( \alpha = 5 \) and 15 % and to \( Q_{a,PET} = 14.7 \text{ L/min} \) for the maximum replacement rate of \( \alpha = 30 \) %. The main air flow rate for propane-air mixture \( Q_{a,m} \) is, therefore, defined by the difference between the total air flow rate \( Q_a \) and the auxiliary air flow rate \( Q_{a,PET} \). As is given in Table 1, the auxiliary air flow is always supplied to prevent a part of propane-air mixture from flowing back to the upstream direction of the PET-powder supply line. PET-powder having an assigned mass flow rate \( m_{PET} \) is, then, supplied to the improved burner and burns as yellow diffusion flame. In this case, three kinds of air flow rates are adjusted so as to satisfy the experimental conditions tabulated in Table 1.

Effects of the replacement rate of PET-powder on the combustion characteristics in the in-furnace operation are examined by observing PET-powder flames in the model furnace and analyzing exhaust gas composition, when PET-powder having a median diameter of \( d_m = 145 \mu \text{m} \) is supplied by varying the replacement rate as \( \alpha = 5, 15 \) and 30 %. Gas Analyzer (TESTO, testo 350 M/XL) is used to measure NOx, O2 and CO concentration. In the highly reducing circumstances, CO/HC-meter (Horiba Seisakusyo, MEXA 324G) is employed to detect CO concentration.

Time-averaged spatial temperature fields are then examined, when PET-powder with a median diameter of \( d_m = 145 \mu \text{m} \) is supplied to the improved burner at the maximum replacement rate of \( \alpha = 30 \) %. As indicated in Fig. 2, three horizontal planes 150 mm apart from each other are set, and temperature is measured at 45 (= 9 \times 5) points in each horizontal plane using an R-type thermocouple of 0.5 mm diameter. No correction is made for measured temperature. Based on the results of point measurements, the spatial temperature field is estimated, whether it can satisfy or not the necessary uniformity for the sintering process.

Effects of the median diameter on the in-furnace combustion characteristics are next examined by varying the median diameter of PET-powder as \( d_m = 89.7, 145 \) and 185 \( \mu \text{m} \) under a constant replacement rate of \( \alpha = 15 \) %. Visual observations and measurements of temperature and exhaust gas concentration are made using the same analyzers.

Finally, effects of PET-powder supply on the whiteness and 3-point bending strength of glazed test species are examined, when they are sintered for an hour under the two extreme conditions of PET-powder replacement rates of \( \alpha = 0 \) % and 15%.

4. Results and Discussion

4.1 Effects of Replacement Rate on In-Furnace Combustion Characteristics

4.1.1 Appearances of PET-powder flames in the model furnace

The improved burner is operated in the model furnace with the replacement rate varied using PET-powder with a median diameter of \( d_m = 145 \mu \text{m} \) and setting the total heat release rate to \( H_t = 11.6 \text{ kW} \) and the overall equivalence ratio to \( \phi = 0.8 \), the latter being considered to be a standard value in the industrial furnace operation \(^6\).

Examples of direct photographs of PET-powder flames are presented in Fig. 4 with the replacement rate varied as a parameter, where (a) gives flame appearances near the burner exit and (b) those near the opposite wall. In every photograph only yellow flames having intense emission relative to the incandescent environmental walls are imaged, since the gas temperature in the furnace is high and the furnace walls become incandescent.

According to Fig. 4(a), independent of the replacement rate, the flame jets issuing from the burner are found to be composed of multiple brilliant stripes of PET particles under gasifying and/or burning. Formation of multiple yellow brilliant flames verifies formation
of a flame zone having locally high equivalence ratio along the jet axis, on the one hand, and initiation of diffusion combustion of gasified PET-resin, on the other. It is also found that the emission intensity from multiple brilliant stripes of flames increases with increasing the replacement rate. This is because that the increase in the replacement rate increases an absolute mass of PET particles having small diameters in the flame zone and, then, also increases generation of gasified PET-resin in the near region of the burner exit.

Direct photographs focused on the opposite wall shown in Figure 4(b), on the other hand, indicate existence of multiple and irregular clusters of flame stripes under combustion, as indicated by each ellipsoid. It is considered that, since PET particles having larger diameters require long time for complete gasification, they reach to the opposite wall without burnout, adhere to the wall and burn as they gasify. The same tendency as observed in Fig. 4(a) is observed concerning the dependency of an absolute mass of PET particles arrived at the opposite wall on the replacement rate. In this case, on the contrary to the case near the burner exit in Fig. 4(a), the increase in $\alpha$ enriches the absolute mass of PET particles having greater diameters and longer life time. This leads to the increase in the number of PET particles attainable to the opposite wall without burnout, being the main reason why multiple and irregular flame stripes become prominent with increasing the replacement rate.

Based on the results mentioned above, it can be understood that the increase in the replacement rate increases simultaneously the absolute mass of PET particles having both smaller and larger diameters and enriches not only multiple brilliant stripes of flames in the near region of the burner exit, but also multiple and irregular clusters of flame stripes in the near region of the opposite wall. In spite of these experimental observations, however, no residual PET-resin is detected adhered to the opposite wall after a long in-furnace operation, even in case of the maximum replacement rate of $\alpha = 30 \%$. This fact indicates that PET particles got to the opposite wall and adhered there are perfectly consumed during the operation in the high temperature furnace. It is concluded here that, even if coarse PET particles having larger sizes would adhere to the surface of sintering materials, no traces of PET particle is left on the product surface and, therefore, the commercial value of products remains almost undamaged.

4.1.2 Behavior of spatial temperature field in the furnace

To examine the uniformity of spatial temperature fields, the improved ceramic burner is operated at the replacement rate of $\alpha = 30 \%$ in the model furnace by setting an objective temperature to $T_i = 1220$ °C. In Fig. 5, sectional profiles of average temperature are presented for (a) those in the upper horizontal plane, (b) those in the middle, and (c) those in the lower, where 45 $(= 5 \times 9)$ grid points give the measuring points. The total heat release rate and the overall equivalence ratio are set to the standard operation condition of $H_t = 11.6$ kW and $\phi = 0.8$. A color scale for evaluating temperature is given at the right lower part of Fig. 5.

According to Fig. 5(a), the sectional profile of time-averaged temperature in the upper
horizontal plane exhibits excellent uniformity varying only in the range of $T_s = 1220 \pm 10 ^\circ C$. In the sectional profiles in the middle and lower horizontal planes, as shown in Figs. 5(b) and 5(c), the temperature uniformity becomes slightly deteriorated due to the local convective effect of intense jet flow from the burner. Even in this case, however, relatively excellent uniformity of $T_s = 1220 \pm 20 ^\circ C$ is realized.

Relatively low temperature of about 1200 $^\circ C$ is detected along the near region about 50 mm apart from the wall, where a series of measuring holes of 15 (= $5 \times 3$) are equipped, as can be seen in Fig. 2, and through which the thermocouple is inserted into the furnace. This is mainly due to heat loss through the thermocouple protection tube made coaxially from stainless and ceramic tubes and having an outer diameter of 20 mm. It is clarified that, anyway, the objective temperature of 1220 $^\circ C$ necessary for the ceramic sintering process is attained within the uniformity of $T_s = 1220 \pm 20 ^\circ C$ by operating the proposed ceramic burner at the replacement rate of $\alpha = 15 \%$.

4.1.3 Variations of exhaust gas temperature and composition

Exhaust gas temperature $T_{ex}$ and concentration of $O_2$, $NO_x$ and $CO$ are measured at the measuring point, which is presented precisely in Fig. 2, under a constant total heat release rate of $H_t = 11.6$ kW. The main air flow rate $Q_{a,m}$ is varied to adjust the overall equivalence ratio in the range of $\phi = 0.63 \sim 1.4$. PET-powder having a median diameter of $d_m = 145 \mu m$ is used as an auxiliary fuel and the replacement rate of PET-powder is varied as a parameter as $\alpha = 0, 5, 15, \text{and } 30 \%$. Results are given in Fig. 6 for (a) exhaust gas temperature, (b) $O_2$ concentration, (c) $NO_x$ concentration and (d) $CO$ concentration, where the abscissa gives the overall equivalence ratio.

Figure 6(a) shows that, when the total heat release rate is kept constant at $H_t = 11.6$ kW, the exhaust gas temperature is hardly influenced by the change of replacement rate and attains its maximum value of about 1400 $^\circ C$ in the range of $\phi = 1.0 \sim 1.2$. $O_2$ concentration shown in Fig. 6(b) also indicates almost no dependency on the replacement rate and becomes negligible small in the fuel rich zone of $\phi > 1.1$, whereas $NO_x$ concentration given in Fig. 6(c) decreases entirely with increasing the replacement rate, being indispensable for clean emission. The gradual reduction of $NO_x$ emission is due to the temperature drop in the main flame zone just downstream of the burner, since the increase in $\alpha$ makes leaner the equivalence ratio of propane-air flame under a constant total equivalence ratio.

In the ceramic industry, highly reducing atmosphere having high $CO$ concentration of 3
~ 5% is indispensable for reducing ferrous impurities in ceramics and for improving the whiteness of the products (7). When PET-powder is used as an auxiliary fuel in the ceramic burner, therefore, the improved burner should possess flexible controllability in the final stage of sintering process. Figure 6(d) clearly verifies that, independent of the replacement rate, extremely high CO concentration up to 5% is obtained by setting the overall equivalence ratio equal to \( \phi = 1.4 \), and that the proposed burner satisfies sufficiently the requirement.

Based on Fig. 5 and Fig. 6(a), the exhaust gas temperature of \( T_{ex} = 1240\degree C \) corresponds to the spatially averaged temperature of \( T_e = 1220 \pm 20\degree C \) under the operation conditions of \( \alpha = 30\% \) and \( \phi = 0.8 \). This correspondence reasonably allows to suppose that the spatial temperature in the furnace may attain to \( T_e = 1300\degree C \), when the proposed burner is operated at \( \alpha = 15\% \) and \( \phi = 1.4 \), satisfying the reducing conditions of the spatial temperature of 1300\degree C and CO concentration of 5%. It is concluded here that the proposed ceramic burner can realize almost the same exhaust characteristics as the original propane fueled industrial burner up to about 30% replacement rate of PET-powder.

### 4.2 Effects of PET-Powder Median Diameter on In-Furnace Combustion Properties

#### 4.2.1 Appearances of PET-powder flames in the model furnace

The improved burner is then operated in the model furnace with the median diameter of PET-powder \( d_m \) varied as a main parameter, by setting the replacement rate to a constant of \( \alpha = 15\% \), the total heat release rate to \( H_t = 11.6 \text{ kW} \) and the overall equivalence ratio to \( \phi = 0.8 \). Examples of direct photographs of PET-powder flames are presented in Fig. 7 with the PET-powder median diameter varied as (i) \( d_m = 89.7\mu m \), (ii) \( d_m = 145\mu m \) and (iii) \( d_m = 185\mu m \), where (a) gives flame appearances near the burner exit and (b) those near the opposite wall. Also in this case only yellow flames with intense emission relative to the incandescent environmental walls are imaged.

Flame appearances near the burner exit given in Fig. 7(a) show that the greater the median diameter becomes, the weaker the emission from the yellow flame becomes. As observed in Fig. 1, PET-powder having a greater median diameter contains many coarser and larger
particles than that having a small median diameter. They need a longer life time and are hard to be completely gasified within the upstream jet region near the burner exit, resulting in inactive diffusion combustion of gasified PET-resin. These characteristic behavior produces just the opposite flame appearances around the opposite wall region, as indicated by each ellipsoid in Fig. 7(b).

Direct photograph in Fig. 7(b)-(i) supplied with PET-powder having the smallest median diameter of $d_m = 89.7 \, \mu m$ exhibits almost no PET particle impinging on the opposite wall, indicating that almost all PET particles are gasified and disappear during their passage ways of 700 mm long through high temperature region in the furnace. As the PET-powder median diameter increases, however, a great number of PET particles impinges on the opposite wall without gasified and burn-up. In case of the flame supplied with PET-powder having the largest median diameter of $d_m = 185 \, \mu m$, as can be seen in Fig. 7(b)-(iii), a great number of PET particles violently impinges on the opposite wall as they burn. The same considerations as those made in Chap. 4.1 can also be adopted here.

**Fig. 8** Effects of PET-powder mean diameter on exhaust gas properties, where $H_t = 11.6 \, kW$, $\phi = 0.8$, $\alpha = 15\%$

- **(a)** Exhaust gas temperature
- **(b)** $O_2$ concentration
- **(c)** NOx concentration
- **(d)** CO concentration

Fig. 7 Effects of PET-powder mean diameter on the in-furnace combustion, where $H_t = 11.6 \, kW$, $\phi = 0.8$, $\alpha = 15\%$
longer time for complete gasification reach to the opposite wall without burnout, adhere to there, and burn as they gasify.

In spite of these experimental observations, by the way, no traces of residual PET-resin is detected adhering to the opposite wall without burnout after a long in-furnace operation, independent of the median diameter of PET-powder. This fact clarifies that PET particles got to the opposite wall and adhered there are perfectly consumed during a long residence time in the high temperature furnace.

4.2.2 Effects of PET-powder median diameter on exhaust gas properties

Exhaust gas temperature $T_{ex}$ and concentration of $O_2$, NOx and CO are measured at the prescribed measuring point by varying the median diameter of PET-powder $d_m$ varied as a parameter under the standard condition of the replacement rate of $\alpha = 15 \%$ and the total heat release rate of $H_t = 11.7$ kW. The results are presented in Fig. 8 for (a) exhaust temperature $T_{ex}$, (b) $O_2$ concentration, (c) NOx concentration and (d) CO concentration, where the abscissa means the overall equivalence ratio. In each figure those data measured without PET-powder supply are also given using an open circle.

Figure 8 shows that, also in the case when the median diameter $d_m$ of PET-powder is varied with its replacement rate kept constant at $\alpha = 15 \%$, the variation of $d_m$ exerts almost no influence on the exhaust characteristics, and that, without any deterioration in the wide controllability of atmosphere from oxidizing to reducing, almost the same behavior of exhaust gas properties is obtained as that measured in the in-furnace operation using only propane as a fuel. It is concluded that such PET-powder as having a relatively large median diameter of $d_m = 185 \mu m$ can be used effectively in the ceramic industries as an auxiliary fuel.

4.3 Comparison of Whiteness and Bending Strength of Test Species

A series of reducing processes of glazed test species are carried out following the under-mentioned procedures.

(a) Adjusting temperature to the objective value of 1300 °C necessary for reduction
(b) One hour sintering operation after setting temperature and CO concentration to each assigned value of 1300 °C and 5 %.
(c) Slow cooling of the in-furnace temperature by adjusting only the air flow rate after stopping the main and/or auxiliary fuel.

Two types of sintering conditions are attempted here; (1) one is an original sintering operation using only propane as a fuel and setting the overall equivalence ratio of $\phi = 1.4$, CO concentration of 5 % and the replacement rate of $\alpha = 0 \%$, and (2) the other is a proposed sintering operation using PET-powder as an auxiliary fuel and setting the overall equivalence ratio of $\phi = 1.4$, CO concentration of 5 % and the replacement rate of $\alpha = 15 \%$.

In Figs. 9(a) and (b), comparison of the whiteness and 3-point bending strength of glazed test species are given, where the above-mentioned two extreme cases are presented.

![Fig. 9](image-url)  
Fig. 9  Comparison of the whiteness and bending strength without and with PET-powder supply ($\alpha = 15 \%$)
by the number (1) and (2), respectively. The whiteness of the standard glazed whiteness board is given in Fig. 9(a) by an abbreviated description of S.M.B. According to Fig. 9(a), although the values of whiteness obtained in the two extreme cases are smaller than the value of S.W.B by about 20%, the difference in whiteness between the two is negligible small. Taking account of the fact that the whiteness can be improved by adjusting the initiation timing and atmospheric condition (8), there is no problem concerning the effect of PET-powder combustion on the whiteness of glazed test species after sintering process.

The 3-point bending strength indicated in Fig. 9(b), on the other hand, takes a value of 52.5 MPa, being slightly smaller than that obtained without PET-powder supply of 56.7 MPa. Although these values of 3-point bending strength are smaller by about 20 ~ 30% than those of the original non-glazed test pieces of 65 ~ 75 MPa, the bending strength of the glazed test species obtained in this paper using the model furnace is estimated to be sufficiently high and reasonable for tableware ceramics.

5. Brief Considerations

According to visual observations using video movies in the model furnace, in spite that high temperature atmosphere is maintained throughout the operation, there are many PET particles impinging on the opposite wall and burning there. To estimate qualitatively the limit diameter of PET particle which impinges the opposite wall without burnout, the mass-based histograms of PET-powder given in Fig. 1 are transformed to the particle number-based distributions, by assuming all PET particles are spherical.

By denoting the density of PET-resin as $\rho_{\text{PET}}$ [kg/m³], the particle mean diameter in an arbitrary $i$-th step of the mass-based histogram in Fig. 1 as $X_i$ [µm], the mass of particles in the $i$-th step of the histogram per unit mass of PET-powder as $m_i$ [kg], the particle number having a mean diameter of $X_i$ as $n_i$, and the total particle number as $N$, the particle number fraction of $X_i$ to the total particle number $N$ is given by the following expression.

$$q_0 = \frac{n_i}{N} = \left[\frac{m_i}{\pi (X_i)^3 \rho_{\text{PET}}} / 6\right] / N \quad (3)$$

The particle number distributions of virtual spherical PET particles transformed using Eq. (3) are presented in Fig. 10, where the ordinate means the particle number fraction and the profiles for three PET-powder median diameters of $d_m = 89.7$ µm, 145 µm and 185 µm are given by a solid line, a broken line, and a chain line, respectively. According to Fig. 10, it can be seen that the distribution is found to be shifted to the large diameter side as $d_m$ increases, and that the large difference in the particle number fraction appears mainly in the range of $X_i \geq 100$ µm. Detailed observation in the latter range clarifies further that PET-powder having $d_m = 89.7$ µm contains almost no particles larger than 200 µm, and that, as $d_m$ increases, a larger number of particles having diameters larger than 200 µm is contained in the PET-powder. The spatial variation of PET-flame appearances with increasing $d_m$, which was already discussed in Section 4.2.1, can be attributed to the change in the particle number fraction of those PET particles having larger diameters than 200 µm.
6. Concluding Remarks

In this paper the effects of the replacement rate $\alpha$ and the median diameter of PET-powder $d_m$ on the in-furnace combustion characteristics of the proposed ceramic burner are examined using PET-powder as an auxiliary fuel, and the applicability of PET-powder to the ceramic industrial burner as one of the alternative fuels is estimated. To verify the validity of PET-powder as an auxiliary fuel in the ceramic industry, the whiteness and 3-point bending strength of the glazed test species sintered under the two extreme conditions of $\alpha = 0\%$ and $\alpha = 15\%$ are also compared with the standard specimens.

It is concluded that, within the experimental ranges of the replacement rate of $\alpha \leq 30\%$ and the median diameter of PET-powder of $d_m \leq 185\mu m$, PET-powder can be applicable to one of the alternative fuels in the ceramic industry. When the proposed burner is operated using PET-powder as an auxiliary fuel under the cold atmospheric condition, however, a large amount of PET particles having larger diameters is exhausted without completely gasified and burnout. Further devises and fundamental studies are, therefore, necessary for decreasing unburnt particle emission, in order to augment the possibility and validity of thermal recycling of PET-powder.

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