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Pyrolysis of COVID-19 disposable masks and catalytic cracking of the volatiles

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1. Introduction

With more than 130 billion disposable medical face masks consumed every month to against COVID-19 epidemic, their efficient recycling and utilization are required not only by public safety, but also by environmental protection and resource utilization [1]. These masks are composed of non-woven fabric, ear band and nose bridge strip. The non-woven fabric has three layers, namely the inner hydroscopic layer, the middle core filter layer and the outer water resistance layer. The hydroscopic and water resistance layers are made of a special polypropylene resin while the filter layer is made of a metal or a metal-plastic composite [2].

The used masks must be treated with great care. A simple method is incineration for energy, but its value is low and the flue gas needs to be treated to eliminate toxic and harmful substances including dioxins [3]. A high value and more efficient method is pyrolysis that converts the masks into useful chemicals and clean fuels at temperatures much lower than that of incineration. Pyrolysis of waste polypropylene has been studied in the past, including thermal, catalytic, thermal plus catalytic in batch and semi-batch reactors [4]. Most pyrolysis was carried out in the temperature range of 425–500 °C to obtain liquids with yields of 67–85.5 wt% [5–7].

Since the early 2021, a few studies reported pyrolysis of disposable medical masks, including those specifically on the non-woven fabric and ear bands [8], the devolatilization kinetics [9], the gas products under different atmospheres [10], the volatiles composition in catalytic pyrolysis [11], and the products in co-pyrolysis of the masks with food waste [12] or medical gloves [13]. For instances, Park et al. [12] reported an oil yield of 59 wt% and a gas yield of 41 wt% at 700 °C while Lee et al. [11] reported an oil yield of 80.7 wt% and a gas yield of 10.1 wt% at 550 °C. They also showed that catalysts with large pores and rich acid centers increased the product’s aromatic content. Park et al. [12] also reported an oil yield of 30 wt% and a gas yield of 49 wt% from co-pyrolysis of the masks with food waste at 900 °C, while Aragaw et al. [13] reported an oil yield of 75 wt% and a gas yield of 10 wt% for co-pyrolysis of the masks with surgical gloves at 400 °C.

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Most of the studies show that the main products are oil with less amounts of gas and a little coke. The oil can be transformed online into gas, light oil and coke through catalytic cracking of the volatiles, which is crucial for the production of high-value added products. However, all the literature studies did not present full oil analysis and failed to report the presence of large amounts of heavy fraction in oils, which cannot be "seen" by most of gas chromatography (GC) analyses and trapped in GC columns. In other words, the oils reported so far are only the light effluent fractions of GC. As a result, the catalytic cracking of volatiles in literatures did not address the conversion of heavy fractions invisible by GC, but it is a must for industrial application.

This paper studies the pyrolysis of whole disposable masks in a two-stage fixed-bed reactor, pyrolysis of the mask sample in the first stage and catalytic cracking of volatiles in the second stage. The yields and composition of gas and liquid products are studied in detail, with emphasis on the conversion of heavy fractions invisible by the GC.

2. Materials and methods

2.1. Material

The COVID-19 disposable masks are from Hangkang Medical Device Co., Ltd (Zhejiang Province, China). They were boiled in water for 2 h, dried at 100 °C for 2 h and separated into three parts. The non-woven fabric of the mask was cut into pieces of about 5 mm in size. The nose bridge strip and the ear band were cut into strips of about 5 mm in length. The mass ratio of the three parts in each mask is about 78:13:9. The inorganic matter (metal rack in nose bridge strip) accounts for 6.0 wt% of the total mask. Table 1 is the ultimate analysis results of the three parts.

Five oxides (Al$_2$O$_3$, kaolin, Fe$_2$O$_3$, CeO$_2$, TiO$_2$) and four molecular sieves (HZSM5, HY, β(25H), β(60H)) were used as the catalysts in the cracking of pyrolysis volatiles. The former were purchased from Macklin (Shanghai, China) and the latter were from XFNANO (Jiangsu Province, China). They were calcined at 500 °C for 3 h in air atmosphere and then ground and sieved to a size of less than 30 µm before the experiment.

### Table 1

| Sample          | Material       | C   | H   | N   | S   |
|----------------|----------------|-----|-----|-----|-----|
| Non-woven fabric | polypropylene | 86.72 | 13.10 | 0.17 | 0.01 |
| Ear band        | polyamide      | 92.38 | 7.18  | 0.43 | 0.01 |
| Nose bridge strip | polyethylene   | 85.73 | 14.14 | 0.09 | 0.05 |

Fig. 1. A schematic diagram of the experimental device.
placed in an ice-water bath. The gas products from the U-tube were collected in a 2 L gas bag. In all the experiments, the heating rate of the first stage was automatically determined by setting the final temperature and the heating was stopped after 1 min at the final temperature. The temperature profiles of the first stage at different final temperatures are shown in Fig. S1.

Two parallel pyrolysis experiments were carried out under each condition. The reactor and the U-tube of one experiment were washed with about 16 g tetrahydrofuran (THF) while the other was washed with about 10 g of n-hexane. Following the traditional definition, the THF soluble liquids are the total liquid product containing oils and asphalts (pre-asphaltenes and asphaltenes) while the n-hexane soluble liquids are oils in the liquid product.

2.3. Quantification of the products

The yields of pyrolysis products were determined by their mass changes against the mass of total organic matters in the mask sample \( m_{\text{organic}} \) in percentage. The yield of solid product \( Y_{\text{solid}} \) was calculated through Eq. (1) where \( m_{\text{solid}} \) and \( m_{\text{inorganic}} \) are the mass of the solid product and the inorganic matter in the mask, respectively. The relative standard deviation of \( Y_{\text{solid}} \) is lower than 1.3%.

The liquid product and the oil are distributed in the outlet of the reactor and the U-tube. Before being washed with THF or n-hexane, the reactor and the U-tube were weighed separately. After being washed with THF or n-hexane, the reactor and the U-tube were dried at 100 °C for 1 h and then weighed. The mass of liquid product in the reactor \( m_{\text{liq}}, \) and in the U-tube \( m_{\text{liq}, \text{U}} \) were determined by differences of the reactor and the tube before and after THF washing and drying, respectively. Similarly, the mass of oil in the reactor \( m_{\text{oil}}, \) and in the U-tube \( m_{\text{oil}, \text{U}} \) were determined by differences of the reactor and the U-tube before and after n-hexane washing and drying, respectively. The yield of liquid product \( Y_{\text{liquid}} \) was calculated using Eq. (2) and the relative standard deviation is lower than 3.8%. The oil yield \( Y_{\text{oil}} \) was calculated using Eq. (3) and the relative standard deviation is lower than 3.5%.

The mass of coke deposited on the catalyst and quartz cotton in the second stage \( m_{\text{coke}} \) was also determined by mass difference before and after the reaction. The yield of coke \( Y_{\text{coke}} \) was determined using Eq. (4) and the relative standard deviation is lower than 4.2%. The yield of gas product \( Y_{\text{gas}} \) was determined according to the mass balance of mask using Eq. (5).

\[
Y_{\text{solid}} = \frac{m_{\text{solid}} - m_{\text{inorganic}}}{m_{\text{organic}}} \times 100\% \quad (1)
\]

\[
Y_{\text{liquid}} = \frac{m_{\text{liq}} + m_{\text{liq}, \text{U}}}{m_{\text{organic}}} \times 100\% \quad (2)
\]

\[
Y_{\text{oil}} = \frac{m_{\text{oil}} + m_{\text{oil}, \text{U}}}{m_{\text{organic}}} \times 100\% \quad (3)
\]

\[
Y_{\text{coke}} = \frac{m_{\text{coke}}}{m_{\text{organic}}} \times 100\% \quad (4)
\]

\[
Y_{\text{gas}} = (1 - Y_{\text{solid}} - Y_{\text{liquid}} - Y_{\text{oil}} - Y_{\text{coke}}) \times 100\% \quad (5)
\]

To understand the mutual effect of the three parts of the mask during pyrolysis, the theoretical yield was estimated according to the product yield and the proportion of each part using the Eq. (6).

\[
Y_{\text{theo}} = \left( \frac{Y_{\text{mask}} \times \text{mask fabric}}{94} + \frac{Y_{\text{ear band}} \times 13}{94} + \frac{Y_{\text{nose bridge strip}} \times 3}{94} \right) \times 100\% \quad (6)
\]

2.4. Characterisation of the products

The compounds in the liquid product and the oil were identified by GC coupled with mass spectrometry (MS) (Agilent 7890B/5977A). The carrier gas was N\textsubscript{2}, split ratio was 20:1, injection volume was 1 µL and the injector temperature was 300 °C. The temperature of GC column was from 40 to 100 °C at a rate of 10 °C/min, from 100 to 300 °C at a rate of 20 °C/min and then hold at 300 °C for 20 min. The ion source temperature of MS was 250 °C and the mass/charge ratio (m/z) was 30-500.

The compounds in the liquid product and the oil were quantified by GC (Agilent 7890B) equipped with a HP-5 capillary column (30 m × 0.32 mm × 0.25 µm) and a FID detector. The GC setting conditions are the same as above except a lower injector temperature, 250 °C. The chromatogram was calibrated by C8-C16 n-paraffins (Table S1 and Table S2 in the supplementary material) to determine the yield of compounds visible by GC. The compounds trapped in the GC column are defined as the column residue and quantified by the difference between the yield of liquid product or the oil and the yield of compounds visible by GC.

The liquid product was also analyzed by two professional organisations using GC-MS (Agilent 6890N/5973) to identify the composition of column residual. One is DB-WAX column (30 m × 0.32 mm × 0.50 µm) with a temperature profile from 40 °C to 300 °C at a rate of 2 °C/min. The other is OV-1 column (30 m × 0.25 mm × 0.25 µm) with a temperature profile from 40 °C to 350 °C at a rate of 25 °C/min. Other GC conditions are the same as above.

The gas products were quantified by a GC (Agilent 7820B) with an Al\textsubscript{2}O\textsubscript{3} capillary column (50 m × 0.53 nm × 10 µm) at a constant temperature of 80 °C and an injection volume of 0.4 mL. The carrier gas was N\textsubscript{2} at a flow rate of 30 mL/min. The injector temperature was 200 °C and the FID temperature was 250 °C. The quantity of gas products was calibrated by an external standard method (see Table S3 in the supplementary material). Three parallel samples were analyzed at each reaction condition to reduce the experimental error.

2.5. Catalyst characterisation

The acidic property of the catalysts was measured using temperature programmed desorption of ammonia (NH\textsubscript{3}-TPD). Before each measurement, the catalyst was in-situ activated at 500 °C for 2 h in Ar atmosphere (50 mL/min) and cooled down to 100 °C. 0.5% NH\textsubscript{3} was introduced for NH\textsubscript{3} adsorption for 1 h, and then switched to Ar for purging. Finally, NH\textsubscript{3} desorption was performed at a heating rate of 10 °C/min from 100 °C to 500 °C. The outlet gas of the reactor was measured continuously by an on-line mass spectroscopy (Ominstar 200, Balzers).

The pore properties of the catalyst were measured using N\textsubscript{2} adsorption at –196 °C on Micromeritics ASAP 2460. The specific surface area
was calculated according to the BET equation. T-plot method and BJH method were used to obtain the total pore volume and average pore size distribution, respectively.

3. Results and discussion

3.1. Thermal pyrolysis

3.1.1. Product yield and gas composition

Fig. 2 shows the product distribution of the mask sample in thermal pyrolysis at different final temperatures, i.e. no catalyst in the second stage. It is seen that the yields of liquid and gas products are about 56.6 and 9.9 wt% at 400 °C, respectively. A higher final pyrolysis temperature increases the yields of liquid and gas products up to 440 °C, being 74.7 wt% and 23.4 wt%, respectively. A little solid residual is detected at 440 °C, about 1.9 wt% of the total mask. At temperatures higher than 440 °C, the yield of liquid decreases very slightly and the yields of gas and solid increase very slightly. This phenomenon indicates that the pyrolysis of mask basically completes at 440 °C and a higher temperature leads to partial cracking of heavier volatiles or conversion of THF-soluble liquid to gas and solid even in the absence of a catalyst. It should be pointed out that the oil accounts for 56–60% of the liquid product at all the temperatures, corresponding to the yield of 29.9 wt% at 400 °C and 42.1 wt% at 440 °C.

Fig. 3 shows the composition of gas products obtained from the experiments in Fig. 2. The bar is the yield of different gas quantified by GC. It is seen from Fig. 6(a) that the identified compounds by GC are apparently less than the column residue in the liquid product. The former slightly increase while the latter significantly increases with increasing the reaction temperature from 400 °C to 420 °C. At 440–580 °C, the yield of the identified components C6–C35 fluctuates at 20.5–22.4 wt% and the yield of column residue fluctuates at 50.8–53.2 wt% (corresponding to 70.0–72.2% of the liquid product).

The oil (n-hexane soluble liquid) is also dominated by the column residue, which again indicates that n-hexane could dissolve some heavy liquids and even asphalt, although the n-hexane soluble liquid is traditionally defined as the oil. At pyrolysis temperatures of 440–580 °C, the identified components C6–C35 totaled 12.1–13.7 wt% and the column residue totaled 30.0–31.2 wt%. It should be noted that the large amount of column residue in the liquid product and the oil is ignorance in many literatures. For example, Miskolczi et al. [4] and Jiraroj et al. [14] used the peak area normalization method to show the selectivity of liquid components. In these cases, the yields of products visible by GC are overestimated or the liquid products’ composition is incorrect.

3.1.2. The liquid products

Fig. 4 shows the GC spectra of the liquid and oil products from the pyrolysis experiment at 440 °C, where the compounds have been identified by GC-MS. It indicates that the compounds and their distribution in the liquid product (THF-soluble) and oil (n-hexane-soluble) are very similar. This phenomenon is surprising because the yields of the liquid and oil are very different (see Fig. 2). Totally, the carbon numbers detected by GC-MS range from C6 to C35 in both liquid product and oil and n-alkanes are dominant with little alkanes and dienes. These phenomena are similar to the polypropylene pyrolysis studies reported by Kassargy et al. [6], Abbas et al. [15] and Soják et al. [16]. The C9+ compounds in the liquid and oil products may be trapped in the GC column and “invisible” by the GC which are termed column residue. In order to understand the nature of column residue, the THF-soluble liquid generated from the pyrolysis at 440 °C was analyzed by two institutions specializing heavy liquid analysis. Results showed the presence of C30–C70 compounds in addition to C9–C35 (Fig. 52). These heavy compounds are possibly asphalt components [17], having a molecular weight of about 500–980 g/mol.

The peaks' height in Fig. 4 preliminarily indicates that C15 alkene is richest and C9, C12 and C15–C25 compounds are relatively richer than other identified components at the final reaction temperature of 440 °C. The yields of each visible compound at different reaction temperatures were quantified by GC and the results are shown in Fig. 5, where the compounds with the same carbon number are grouped and those with a retention time longer than 21 min are combined as C22–C30. In the liquid product, the yields of C7, C8, C9, C11 and C17 compounds are less than 0.5 wt% and roughly not influenced by the reaction temperature. The C15 yield is the largest, increasing from 3.4 wt% at 400 °C to 4.8 wt% at 440 °C and decreasing to 3.7 wt% at 540 °C. The yields of other compounds basically increase with the reaction temperature from 400 °C to 440 °C and keep constant or decrease with further increasing the reaction temperature.

The yields of C7–C25 compounds in the oil product are similar to the counterparts in the liquid product, while the yield of each C15+ component in the oil product is lower that of the same compound in the liquid product, for example, 2.7 wt% vs. 4.8 wt% for C15 at 440 °C. This phenomenon indicates that n-hexane could dissolve some larger liquid components but with a lower solubility than THF.

The relatively more C15 product can be explained by the mechanism proposed by Luda et al. [18]. They reported that the pyrolysis produces mainly n-alkenes through intramolecular hydrogen transfer of secondary radicals, including the transfer from the first C to the third, fourth, fifth and sixth C. Among them, the activation energy required for the transfer to the fifth C is the lowest and two of this hydrogen transfer will generate C15 through β-bond fracture. For this reason, C15 is the most abundant liquid product in the pyrolysis experiment of polypropylene.

The yields of total identified compounds and column residue at different reaction temperatures are shown in Fig. 6. It is seen from Fig. 6(a) that the identified compounds by GC are apparently less than the column residue in the liquid product. The former slightly increase while the latter significantly increases with increasing the reaction temperature from 400 °C to 220 °C. At 440–580 °C, the yield of the identified components C6–C35 fluctuates at 20.5–22.4 wt% and the yield of column residue fluctuates at 50.8–53.2 wt% (corresponding to 70.0–72.2% of the liquid product).

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little and the liquid product is the most. By contrast, nose bridge strip generated more liquid and less gas while non-woven fabric generated less liquid and more gas. According to the proportion of each part in mask, theoretical yields of mask pyrolysis were calculated using Eq. (6) and the results are shown in Table 2. The theoretical liquid yield is slightly higher than the experimental yield of the mixture, while the theoretical gas yield is slightly lower than the experimental yield. The differences are between 1.0 and 2.3 wt%. Fig. 7 compares the theoretical and experimental yields of C$_3$H$_6$, C$_4$H$_8$, C$_5$ and C$_{15}$ hydrocarbons at the pyrolysis temperature of 440 °C. The theoretical values of C$_3$H$_6$, C$_4$H$_8$ and C$_{15}$ are slightly higher than their experimental values, and the theoretical C$_5$ yield is slightly lower than the experimental yield. The differences of them are less than 1 wt%. This information suggests little interaction between the three parts during the mixture pyrolysis.

3.2. Pyrolysis followed by catalytic cracking of volatiles

The volatiles’ reaction in pyrolysis of many organic matters has been reported to be a crucial step to determine the final products [19–21]. It is also important in mask pyrolysis to covert the heavy volatile components, especially the column residue, to light compounds in order to raise the pyrolysis efficiency, which may be accomplished by in situ cracking of volatiles over a catalyst. According to the literatures [22–29], oxides (Fe$_2$O$_3$, Al$_2$O$_3$ and kaolin) and molecular sieves (β(25 H), β(60 H), HZSM5 and HY) were evaluated in this work. TiO$_2$ and CeO$_2$ were tested for comparison. The catalysts were loaded in the second stage of the reactor.

3.2.1. Effect of oxide catalysts on cracking of volatiles

It should be pointed out that the oxides in the second stage have little influence on the solid residual in the first stage and its amount fluctuates at 1.7–2.0 wt% of the mask in all the runs. The coke deposited on the catalysts is also very little and less than 0.6 wt% of the mask. Therefore, the solid residual and coke will not be discussed. Fig. 8 shows the effect of oxides on the yield and distribution of gas product at a cracking temperature of 440 °C. The overall yields of organic gas determined by GC (the bars) are slightly less than those determined by mass balance (the square symbols). These differences may be attributed to the
formation of H$_2$ and other minor gases as reported in literature [4]. In comparison to "no catalyst", all the catalysts increase the gas yield, especially C$_5$, propylene (C$_3$H$_6$) and butene (C$_4$H$_8$), indicating cracking of heavy volatiles. The catalysts differ in activity but result in similar gas components. TiO$_2$ has the largest catalytic effect as shown by the largest

**Table 2**
The product yield from pyrolysis of the three parts of the mask.

| T (°C) | Feedstock                                      | $Y_{\text{solid}}$ (wt %) | $Y_{\text{liquid}}$ (wt %) | $Y_{\text{gas}}$ (wt %) |
|--------|------------------------------------------------|---------------------------|-----------------------------|--------------------------|
| 440    | Non-woven fabric                               | 1.3                       | 73.6                        | 25.1                     |
|        | Ear band                                       | 4.9                       | 83.8                        | 11.2                     |
|        | Nose bridge strip without metal rack            | 0.1                       | 93.1                        | 6.8                      |
|        | Mask (theoretical)                             | 1.8                       | 75.6                        | 22.6                     |
|        | Mixture of the three parts                     | 1.9                       | 74.7                        | 23.4                     |
| 580    | Non-woven fabric                               | 1.3                       | 72.8                        | 26.1                     |
|        | Ear band                                       | 5.7                       | 81.2                        | 13.1                     |
|        | Nose bridge strip without metal rack            | 0.1                       | 91.9                        | 8.0                      |
|        | Mask (theoretical)                             | 1.8                       | 74.5                        | 23.7                     |
|        | Mixture of the three parts                     | 1.6                       | 72.4                        | 26.0                     |

**Fig. 5.** Effect of the pyrolysis temperature on composition of the liquid product and the oil (a) liquid product (THF soluble product); (b) oil (n-hexane soluble product).

**Fig. 6.** The yields of GC effluent and column residue in the (a) liquid product and (b) oil product.

**Fig. 7.** Comparison of the theoretical and experimental values of the main products at 440 °C.
gas yield increase, from 23.4 wt% in the absence of a catalyst to 38.5 wt%, with C_5 and propylene yields of 18.2 and 8.5 wt%, respectively.

Fig. 9 shows the effect of oxides on the yield and distribution of liquid product at cracking temperature of 440°C. It is seen that all the catalysts reduce the liquid yield, which is consistent with the increased gas yield. TiO_2 has the largest cracking effect as shown by the largest liquid yield decrease, from 74.7 wt% in the absence of a catalyst to 59.6 wt%. The major change by the catalysts is the large reduction in column residue, especially over TiO_2, from about 52.3 wt% without a catalyst to about 37.9 wt%. The yield of C_6-C_35 decreases little, from 22.4 wt% without a catalyst to 21.7 wt% with TiO_2 and to 19.4 wt% with kaolin, for example. The detailed information about C_6-C_35 compounds shown in Fig. 9(b) indicates that C_6 and C_15 are reduced, C_{10} is increased and C_{16}-C_{19} do not change much over all the catalysts, while C_9 is reduced by kaolin and TiO_2.

3.2.2. Effects of molecular sieve catalysts on cracking of volatiles

Similar to the oxide catalysts, molecular sieve catalysts have little influence on the solid residual and the coke deposited on the catalysts is less than 0.7 wt% of the mask. Fig. 10 shows the effect molecular sieves on the yield of gas product and its distribution at cracking temperature of 440°C. It is seen that the gas yield determined by mass balance (square symbols) is similar to the value determined by GC in all the cases except HZSM5 where the difference is about 2.0 wt% due to H_2 and other minor gases not included in the GC analysis. In comparison to “no catalyst”, all the molecular sieves increase the gas yield. HY and β(60 H) are the most active ones and increase the gas yield from 23.4 wt% to 42.1 and 43.4 wt%, respectively. The component of the largest yield increase is butene, followed by propylene and butane. The yield of butene is as high as 16.5 wt% for HY and 17.6 wt% for β(60 H). The yield of C_6 decreases slightly from 12.5 wt% to 10.0 wt% in the presence of molecular sieve catalysts. These results are significantly different from those of the oxide catalysts in Fig. 8 where the yield of C_6 increases.

Fig. 11 shows the yield and composition of the liquid products obtained from the experiments in Fig. 10. All the molecular sieve catalysts reduce the yield of the liquid product with HY and β(60 H) as the most active ones. The liquid yield decreases from 74.7 wt% in the absence of a catalyst to 55.0 wt% over HY and β(60 H) catalysts. The difference of 19.7 wt% (74.7 minus 55.0) is similar to the increased gas yield 20.0 wt% (Fig. 10), indicating cracking of volatiles in liquid sizes to the gas product. Specifically, both the C_6-C_35 compounds and the column residue are reduced, about 9% points to 13.5 wt% and about 11% points to 41.5 wt% over HY and β(60 H). Fig. 11 (b) indicates that the reduced C_6-

![Fig. 8. Effect of oxide catalysts on the yield and distribution of gas product at 440°C.](image)

![Fig. 9. Effect of oxide catalysts on the yield and distribution of liquid product at 440°C. (a) Yields of C_6-C_35 and column residue and (b) distribution of C_6-C_35.](image)

![Fig. 10. Effect of molecular sieve catalysts on the yield and distribution of gas product at 440°C.](image)

![Fig. 11. Effect of molecular sieve catalysts on the yield and composition of liquid products obtained from the experiments in Fig. 10.](image)
Fig. 11. Effect of molecular sieve catalysts on the yield and distribution of liquid product at 440 °C. (a) Yields of C₆-C₃₅ and column residue and (b) distribution of C₆-C₃₅.

Fig. 12. Effect of volatiles’ cracking temperature on the liquid and gas products under HY catalyst.

Fig. 13. Effect of the cracking temperature on the liquid and gas products under β(60 H) catalyst.
C₃-compounds are mainly C₉, C₁₂, C₁₅ and C₁₅–C₂₂ except C₁₇ over β(60 H) catalyst. These data indicate that the molecular sieve catalysts are somewhat better than the oxide catalysts in column residue conversion and C₃–C₄ alkene formation.

3.2.3. Influence of catalytic cracking temperature on products distribution

The activities of HY and β(60 H) were further studied at higher temperatures, 500–580 °C, where the temperature of mask pyrolysis in the first stage was kept at 440 °C. Fig. 12 shows the yield and composition of the liquid and gas products under HY catalyst. It is seen that the yield of liquid product keeps at about 55.0 wt% with increasing the cracking temperature from 440 °C to 500 °C and decreases to 33.1 wt% and 14.4 wt% at 550 and 580 °C, respectively, indicating significant cracking of the liquid product at 550–580 °C. The C₆–C₁₅ compounds are reduced about 9% points to 4.4 wt% and the column residual is reduced about 32% points to 9.9 wt% at 580 °C. The change of total gas yield with the cracking temperature is opposite to that of the liquid product due to cracking of the liquid to the gas product. The gas yield is similar at 440 and 500 °C, but the gas composition is different, more propane and less butene at 500 °C, which are similar to those of HY catalyst. The yields of butene and propylene are as high as 30.9 wt% and 25.8 wt% at 580 °C, respectively, totally accounting for 65.5% of the gas product. The yield of C₃ is 6.7 wt% and the total yield of C₁–C₂ and propane is 19.2 wt% at 580 °C, which are similar to those of HY catalyst.

3.2.4. Preliminary analysis to the catalysts

It is recognized that the pore size, surface area and acidity of catalyst influence its catalytic ability in volatile cracking [11,27,29,30]. Wei et al. [28] reported that the catalyst with strong acidity would cause the volatile to over-dissociate into more small molecule gases. Table 3 shows the pore properties of the catalysts. It indicates that the surface areas of all molecular sieve catalysts, 346–847 m²/g, are larger than those of oxide catalysts, 9–153 m²/g, while the pore sizes of molecular sieve catalysts, 1.6–2.9 nm, are smaller than those of oxide catalysts, mostly 12.4–16.3 nm and 4.15 nm for Al₂O₃. Fig. 14 shows NH₃-TPD profiles of the catalysts. It is seen that all the oxide catalysts except Fe₂O₃ do not have acidic sites. Among the four molecular sieve catalysts, the acidity of HY is the strongest, followed by HZSM5. The acidities of β(60 H) and β(25 H) are similar and slightly weaker.

The far different properties of oxides and molecular sieves suggest that they may follow different catalytic mechanism. For the oxide catalysts, TiO₂ and kaolin have the smallest surface area, larger pore size and little acidity, but they present higher catalytic activities in volatile cracking. This phenomenon suggests that the catalyst with large pore size is more conducive to the cracking of macromolecules into pores and the advantages of surface area are obscure [22]. For the molecular sieve catalysts, HY has the strongest acidity and good catalytic activity, which seems to suggest the importance of acidity in the cracking of volatiles. However, the good catalytic performance of β(60 H) and weaker acidity do not seem to support the importance of acidity. The relationship between the gas yield with the pore size and surface area of molecular

| Catalyst | BET surface Area (m²/g) | Total pore Volume (cm³/g) | Average pore Size (nm) |
|----------|--------------------------|---------------------------|-----------------------|
| Fe₂O₃    | 109.73                   | 0.11                      | 14.17                 |
| Al₂O₃    | 153.62                   | 0.54                      | 4.15                  |
| CeO₂     | 64.37                    | 0.20                      | 12.36                 |
| Kaolin   | 9.25                     | 0.01                      | 16.16                 |
| TiO₂     | 11.51                    | 0.02                      | 16.34                 |
| β(2SH)   | 552.85                   | 0.40                      | 2.91                  |
| HZSM5    | 376.60                   | 0.17                      | 1.82                  |
| HY       | 847.60                   | 0.36                      | 1.67                  |
| β(60H)   | 566.39                   | 0.17                      | 2.50                  |

Table 3: Pore properties of the catalysts tested in this study.

Fig. 14. NH₃-TPD profiles for the catalysts tested in this study (a) oxide catalysts and (b) molecular sieve catalysts.
sieve catalysts is also obscure, as reported by Choi et al. [25]. These results indicate that cracking of volatile on the molecular sieves is complex and needs more investigation to disclose the most important factor influencing the catalytic activity.

4. Conclusion

Disposable COVID-19 masks can be converted to liquids and light hydrocarbons through a two-stage process. The first stage fully pyrolyzes the masks at 440 °C to generate volatiles composed of 23.4 wt% gas, 74.7 wt% THF soluble liquids or 42.1 wt% n-hexane soluble liquids. The major gas components are C2, followed by propylene and butene, accounting for 54.8%, 22.8% and 14.5% of the gas product, respectively. The THF soluble liquids are composed of about 30% C3-C5 alkenes and about 70% C6-C7 hydrocarbons which are trapped in the GC column (termed column residue).

The second stage catalytically converts the heavy volatiles, especially the column residue, to light oil and gases rich in C3-C6 alkenes. The molecular sieve catalysts are somewhat better than the oxide catalysts in column residue conversion and C3-C5 alkene formation, with β(60 H) as the best one. At cracking temperature of 580 °C (β(60 H)), the liquid yield decreases to 10.2 wt% with 5.3 wt% being C6-C8 compounds and 4.9 wt% being the column residue, and the total gas yield increases to 86.5 wt% with 30.9 wt% being butene and 25.8 wt% being propylene.

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Declaration of Competing Interest

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Appendix A. Supporting information

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