

Decomposition of Thermally Stable Fuel Using a Cerium-Modified Zeolite Catalyst and Endothermic Characteristics

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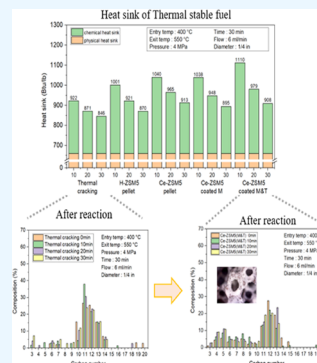
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ABSTRACT: The increase in the speed of aircraft causes a thermal load in the system. A cooling system is needed to solve this. Proactively, research is being conducted to cool the thermal load through the endothermic reaction of aircraft fuel. The decomposition of thermally stable fuel was performed using a lanthanide-modified zeolite as a catalyst, which was coated onto metal foam and the inner wall of a tube reactor to confirm the endothermic characteristics of the catalytic decomposition reaction. When a cerium-modified zeolite was used, the heat sink was increased to 1100Btu/lb and showed excellent performance for the cracking reaction.



1. INTRODUCTION

Owing to advances in technology, the speed of hypersonic aircraft is increasing. An increase in the aircraft speed causes a thermal load on the system. This causes serious problems such as system malfunctions and modification of the foam outside the aircraft;^{1–3} therefore, cooling systems are required to address this problem. Research is being conducted to cool the thermal load through the endothermic reaction of aircraft fuel, which is called endothermic fuel.⁴ The endothermic reaction can be maximized by using catalysts. Zeolite catalyst pellets are commonly used for this purpose. However, in the case of pellets, there is a problem with the low surface area and pressure drop.^{5–7} To improve this, the reaction was performed by coating the catalyst on supports such as metal foam and tube walls. Metal foam is a porous alloy support with the advantage of having excellent thermal stability and a high surface area. A previous study was conducted to improve the characteristics of the endothermic reaction using metal foam as a support for the catalyst.^{8,9} In this study, we compared the performances of modified metals in zeolites with those of existing catalysts, which are often used as catalysts for the manufacture of hydrocarbon fuels.

Lanthanum, samarium, and cerium were used for zeolite modification. All elements used in the modification were lanthanides, which have similar properties. Following modification with lanthanum, the activity and stability of the catalyst increased significantly.^{10,11} In addition, lanthanum produces new acidic sites, which are of significant advantage to this alkylation reaction.¹² Cerium is widely used as a structural promoter or an active component in heterogeneous catalysts

because of its catalytic activity and favorable reducibility.^{13,14} The use of cerium-modified HY zeolite can enhance the stability of the adsorbent structure and its acidity by interacting with BAS.¹⁵ Appropriate cerium consumption promotes hydrogen transfer reactions, and the introduction of cerium increases the LAS/BAS ratio of the catalyst, facilitating the decarbonylation pathway, which improves the performance of the catalyst and promotes hydrocarbon production.¹⁶

As JP-7 has excellent thermal stability, it is often used to prevent the formation of carbon deposits when the fuel is heated. JP-7 is an Air Force jet fuel specification (MIL-T-38219) consisting primarily of paraffin and cycloparaffin with an average carbon number of 12 and limited to a maximum aromatic content of 5 vol %.¹⁷ Thermally stable fuels such as JP-7 have high oxidative stability and inhibit the formation of deposits. As high-temperature aircraft continue to gain prominence, there is a growing demand for fuels of the JP-7 class. Consequently, extensive research is actively being conducted to manufacture thermally stable fuels that meet these requirements.^{18,19}

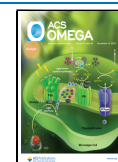
The purpose of this study was to determine the heat sink and coke formation of a thermally stable fuel (JP-7 level) endothermic reaction in a flow reactor using a cerium-modified

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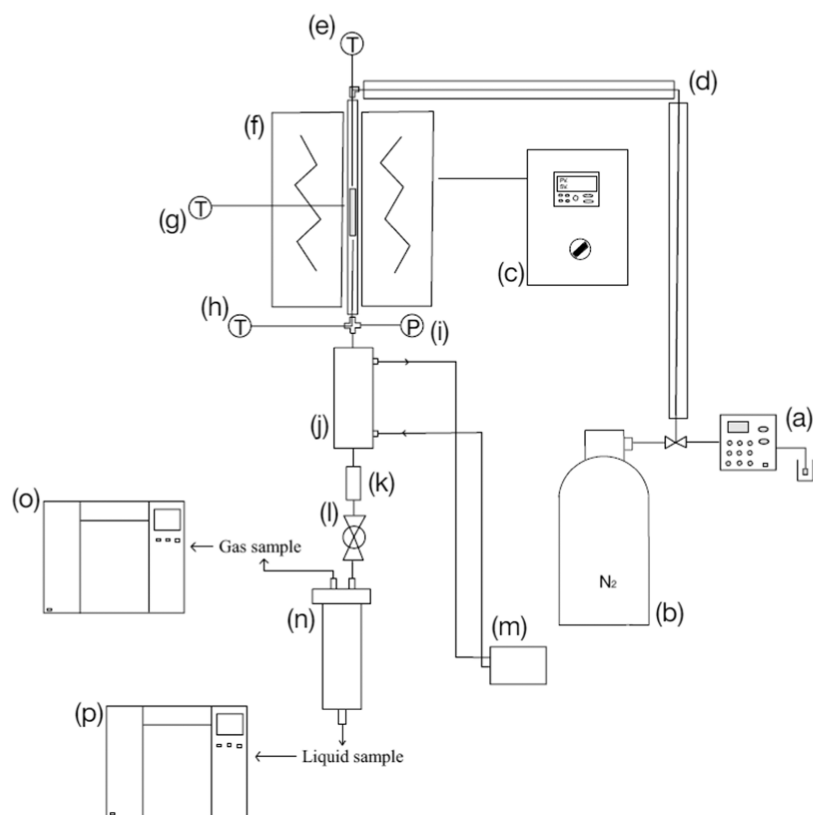


Figure 1. Schematics of the flow reactor: (a) pump, (b) gas, (c) controller, (d) preheater, (e), (g), and (h) thermal couple, (f) heater, (i) pressure gauge, (j) condenser, (k) filter, (l) BPR, (m) cooler, (n) separator, (o) GC-FID, and (p) GC-MS.

catalyst and to compare the endothermic properties of each catalyst.

2. EXPERIMENTAL SECTION

2.1. Materials. NH₃-ZSM5 zeolite (CBV-2314, SiO₂/Al₂O₃ mole ratio = 23) was purchased from Zeolyst. NH₃-ZSM5 zeolite was calcined at 600 °C for 5 h in air to produce H-ZSM5. Lanthanum nitrate hexahydrate (99.99%), cerium(III) nitrate hexahydrate, and colloidal silica binder (LUDOX AS-30, 30 wt % suspension in H₂O) were purchased from Sigma-Aldrich. Samarium(III) nitrate hexahydrate was purchased from Kanto Chemical Co. The metal foam (N10 no. 05 model) support was purchased from Alantum. The stainless steel tube was made of SS 316.

2.2. Methods. **2.2.1. Metal Doping in H-ZSM5.** Zeolite modification was carried out in the same manner using lanthanum, samarium, and cerium. Metal doping proceeded with H-ZSM5, which was calcined to form an NH₃-ZSM5 zeolite at 600 °C for 5 h. The H-ZSM5 (5 g) and metal precursors (La(NO₃)₃·6H₂O, Sm(NO₃)₃·6H₂O, Ce(NO₃)₃·6H₂O) (0.5 mol) were dissolved in distilled water under vigorous stirring at 80 °C for 4 h.¹² Metal-doped ZSM5 was thoroughly washed with distilled water and then filtered and dehydrated at 90 °C for more than 8 h. Finally, the powder was calcined at 600 °C for 5 h in air. The modified ZSM5 samples were denoted as La-ZSM5, Sm-ZSM5, and Ce-ZSM5 and were characterized by X-ray diffraction (XRD), Fourier transform infrared (FT-IR), and NH₃-TPD.

2.2.2. Catalyst Wash-Coated on Metal Foam and Stainless Steel Tubes. The slurry used for La-ZSM5, Sm-ZSM5, and Ce-ZSM5 wash coatings on metal foam contained

82 wt % distilled water, 12 wt % metal-doped ZSM5, and 6 wt % silica binder.⁸ The slurry was stirred thoroughly for more than 2 h. The metal foam was cut into 3 mm widths and 5 cm long and washed with acetone for 15 min using ultrasonication. Following washing, metal foam was dried for 30 min at 150 °C. The dried metal foam was then placed into the slurry for 10 s, followed by air blowing and drying in an oven for 30 min at 150 °C. This process was repeated until the desired catalyst loading was obtained.

Coating slurries used for La-ZSM5, Sm-ZSM5, and Ce-ZSM5 wash coatings on stainless steel tube contained 70 wt % distilled water, 10 wt % metal-doped ZSM5, and 20 wt % silica binder. The slurry was stirred thoroughly for more than 2 h. The 1/4 in. SS tube was cut to 36 cm length, washed with acetone, and dried for 30 min at 150 °C. Blocking one entrance of the tube, the slurry was filled inside the tube for 10 s and allowed to flow, followed by drying in oven for 30 min at 150 °C. This process was repeated until the desired catalyst loading was obtained. The coated metal foam and tubes were calcined at 600 °C for 5 h in air. In this study, 100 mg of the catalyst was loaded onto the metal foam and the SS tube.

2.3. Endothermic Cracking Reaction in a Flow Reactor. Endothermic cracking was performed by using a flow reactor, as illustrated in Figure 1. Before performing the reaction, the preheater temperature was set to 300 °C, and then acetone was shed with a high-performance liquid chromatography (HPLC) pump for 2 h to 4–5 mL/min to clean the reactor. The filter and the 1/4 in. stainless steel tube with the manufactured catalyst were connected to the reactor, and it was checked for gas leakage from the connection. The reactor was purged with nitrogen, and a regulated back pressure regulator (BPR) was used to maintain the pressure

inside the reactor at 40 bar. The preheater was set to 400 °C, and the internal temperature of the reactor was raised to 550 °C for 30 min through the electric furnace. Once the internal temperature of the reactor reached 550 °C, the power was stabilized for 30 min. Subsequently, an endothermic cracking reaction began. The reaction was conducted for 30 min at a flow rate of 6 mL/min with an HPLC pump, using a thermally stable fuel as the reactant. The gas and liquid products were collected every 10 min during the reaction. The sampled gas was analyzed through GC-FID and GC-TCD, and liquid products were analyzed through GC-MS.

Table 1 summarizes the analytical conditions for the gas and liquid products. The power was recorded at 1 s intervals for 30

Table 1. Analysis Conditions of GC-FID and GC-MS

	GC-FID	GC-MS
parameter	setting	
column	GS-Gas Pro	HP-5MS
carrier gas	N ₂	He
injection	0.2 μL	0.2 μL (Split mode)
inlet	250 °C, 4.9 psi	280 °C, 7.1 psi
oven	50 °C (3 min) to 120 °C Rate: 20 °C/min	40 °C (1 min) to 290 °C Rate: 10 °C/min

min. The heat sink was calculated as the 10 min average of the amount of power recorded for 30 min. The carbon deposit, a reaction byproduct generated during the reaction, was analyzed by comparing the weights of the tube, catalyst, and filter after the reaction.

3. RESULTS AND DISCUSSION

3.1. Catalyst Characteristics. Because the catalyst was manufactured by doping H-ZSM5 with metal, it was necessary to determine the differences in the properties of existing H-ZSM5 and the catalyst obtained by doping. The properties of the catalysts manufactured using lanthanum were identified through Brunauer-Emmett-Teller (BET), XRD, FT-IR, and NH₃-TPD. Table 2 summarizes the results of the BET analysis

Table 2. BET Results of Catalysts

catalyst	surface area (m ² /g)	pore size (Å)
H-ZSM5	358	6.56
La-ZSM5	212	21.2
Ce-ZSM5	229	23.6
Sm-ZSM5	227	19.9

of the catalyst. The surface area shows a lower value in the modified catalysts than H-ZSM5. This is a reduction in surface area through metal doping, and the pore size has increased due to the reduction in micropores. The effect of the change in surface area on the result of the decomposition reaction is judged to be insignificant.

Figure 2 is the XRD result confirming the crystallinity of the modified catalyst that underwent the coating process.

It can be observed that all of the catalysts modified with lanthanum, cerium, and samarium have peaks shown for the existing H-ZSM5. This implies that the H-ZSM5 catalyst was not deformed during the modification and coating process. In the cerium regenerative zeolite, new peaks can be found at 28, 38, 48, and 55°, which are in accordance with peaks indicating the coupling of CeO₂.^{20,21} On the other hand, in the case of

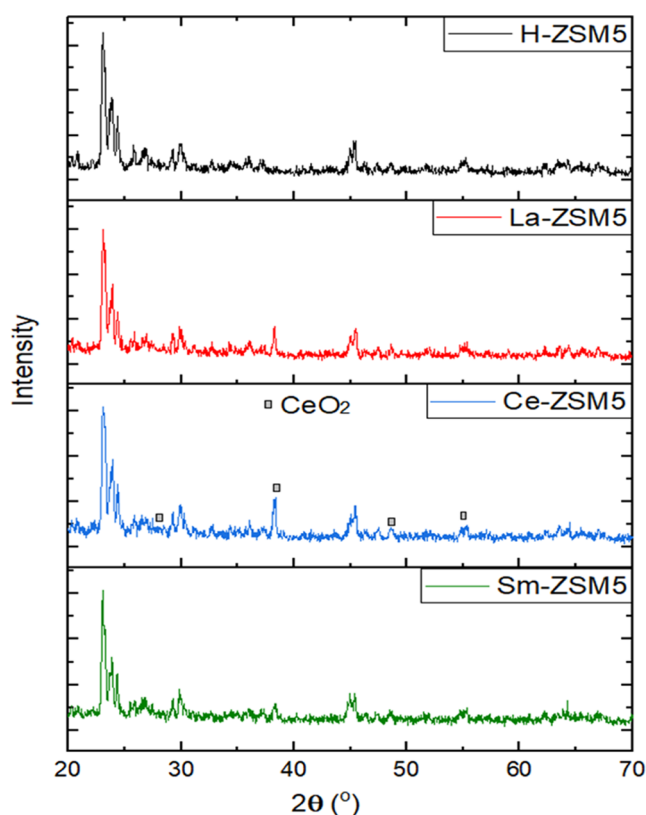


Figure 2. XRD patterns of modified H-ZSM5.

the zeolite modified with lanthanum and samarium, there is no new peak. Increasing the metal doping ratio of lanthanum and samarium deformed the crystallinity of H-ZSM5, resulting in a decrease in the peak intensity.²² The shape of the graph is similar to that of H-ZSM5, indicating that the ratio of metal doping is small.

FT-IR analyses of H-ZSM5 and the manufactured catalysts were conducted to observe the changes in the properties and acid sites of the zeolite, and the results are shown in Figure 3. It can be seen that all three modified catalysts showed the same shape as the existing H-ZSM5 in the vibration region of zeolite, 600–1200 cm⁻¹, and well maintained the functional group of zeolite. In the region of 3500–3850 cm⁻¹, the signal of the OH group can be confirmed. The signal at 3748 cm⁻¹ indicated silanol groups on the external surface.²³ The bands of 3620 and 3780 cm⁻¹ represent Brønsted sites in the OH group.²⁴ Following the metal modification, the peak with a higher intensity was observed than that of the existing H-ZSM5 catalyst. In particular, the ceria-modified catalyst exhibited the highest intensity.

The pyridine adsorption IR results are shown in Figure 4 for further analysis of the catalyst acid site. It can be seen that the 1480–1520 and 1620–1640 cm⁻¹ peaks represent the Brønsted site and the Lewis acid site, 1470 cm⁻¹ peak represents the Lewis acid site, and 1560 cm⁻¹ peak represents the Brønsted site.^{25,26} The peak of H-ZSM5 is relatively broad, and for the catalyst modified with lanthanum and samarium, it is difficult to identify a clear peak that is distinct from H-ZSM5. On the other hand, with the cerium-modified catalyst, the increase in Lewis acid sites and Brønsted sites is observed clearly. Increased acid sites promote the hydrogen transfer reaction and the decarbonylation pathway, which increase the activity of the catalytic reaction.

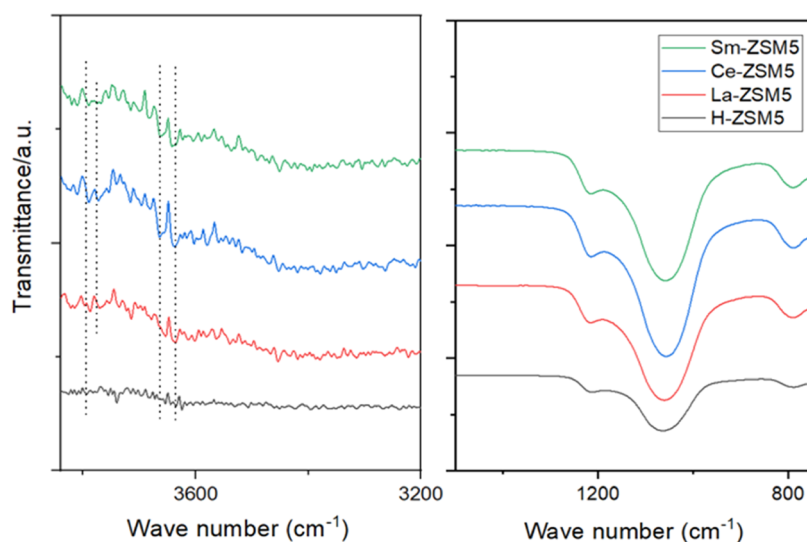


Figure 3. FT-IR spectra of modified H-ZSM5.

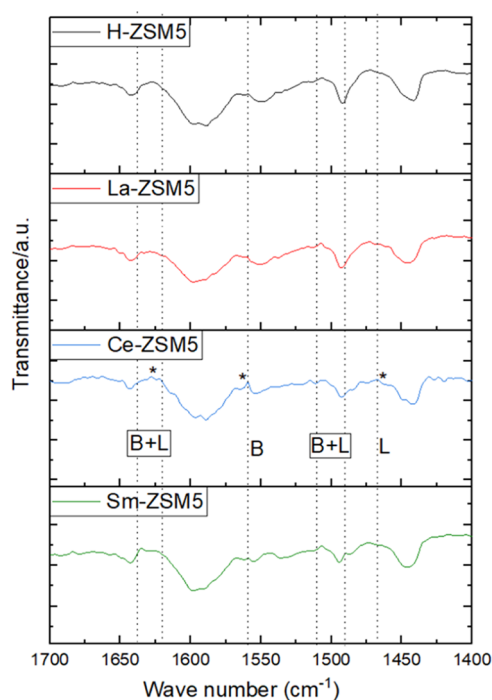


Figure 4. Pyridine adsorption IR of modified H-ZSM5.

Figure 5 shows the results of the NH_3 -TPD analysis that identify the changes in the strong and weak acid sites of the existing catalyst H-ZSM5 and the modified catalyst. NH_3 -TPD analysis was conducted after pretreatment up to 500 °C under He conditions, and the NH_3 adsorption occurred for 1 h at 100 °C; the reactor was purged with He, and the temperature was elevated to 500 °C at He conditions for acid site analysis. Because the number of acid sites of the catalyst is proportional to the activity of the catalyst, the activity decreases when the number of acid sites decreases. Most of the catalysts show reduced number of acid sites through metal doping, which lowers the activity and reduces the degree of catalyst inactivation in the reaction.^{27,28} However, in the case of H-ZSM5 modified with lanthanum, cerium, and samarium, the strong and weak acid site forms of the existing H-ZSM5 were

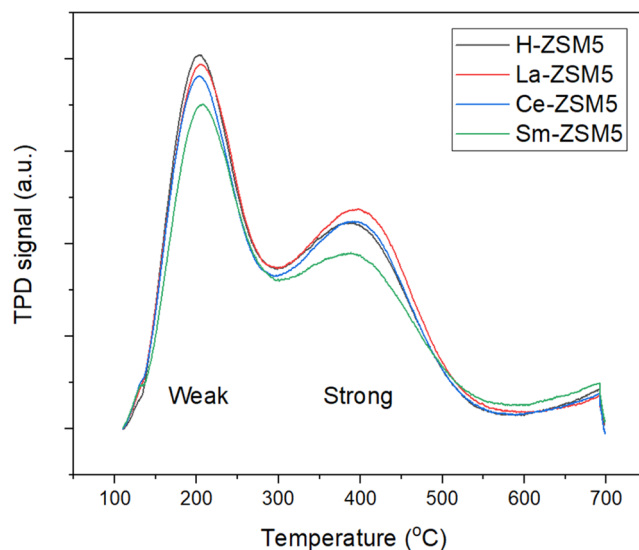


Figure 5. NH_3 -TPD curves of modified H-ZSM5.

maintained. H-ZSM5 modified with samarium had a relatively small number of strong acid sites.

3.2. Thermally Stable Fuel Cracking Reaction.

3.2.1. Efficiency of the Reactor. Heat sinks can be divided into two types: chemical and physical. The physical heat sink required to raise the temperature is theoretically calculated by using a program called a super trap, and the chemical heat sink can be obtained from the amount of power obtained as a result of the reaction. The chemical heat sink is the value minus the basis watt from the amount of water used for 30 min of reaction time. The basis watt is the power consumed by the heater under conditions in which the heat-sink reaction does not progress. Because the electric energy of the heater is not converted to 100% thermal energy, the efficiency value of the heater should be considered when calculating the chemical heat sink. The efficiency value was theoretically obtained at 300 °C where the pyrolysis reaction of the thermally stable fuel did not occur.²⁹ Table 3 shows the efficiency value (η). The efficiency value can be calculated by comparing the experimental value with the theoretical value. The experimental value is calculated by using the amount of power when

Table 3. Efficiency Value of the Thermally Stable Fuel Endothermic Reaction

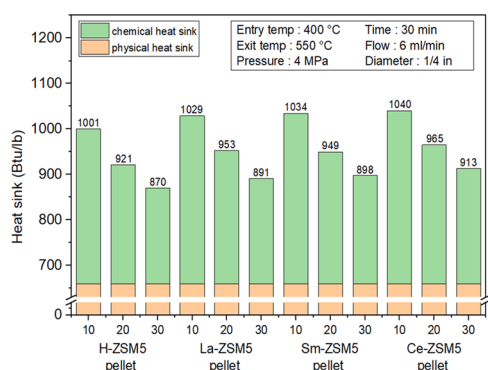
	theoretical value	experimental value	efficiency value (η)
thermal stable fuel	387	1064	0.36

the reaction is performed at 300 °C, and the theoretical value is calculated by using the theoretical heat sink at 300 °C by super trap. When calculating the chemical heat sink, we used the efficiency value. The chemical heat sink is calculated using the following equation.

$$\text{chemical heat sink} = \frac{(W_{\text{reac}} - W_{\text{basis}})}{\text{flowrate}} * \eta \quad (1)$$

3.2.2. Heat Sink of the Decomposition Reaction. H-ZSMS is widely used as a catalyst for liquid hydrocarbon fuels. To confirm the performance of modified ZSMS through the lanthanide element, the heat sink was compared with that of the existing commercial catalyst H-ZSMS.

Figure 6 shows the heat sink for the modified ZSMS through lanthanide elements and the H-ZSMS pellet reacted at 550 °C

**Figure 6.** Heat sink of the endothermic reaction using the modified ZSMS pellet.

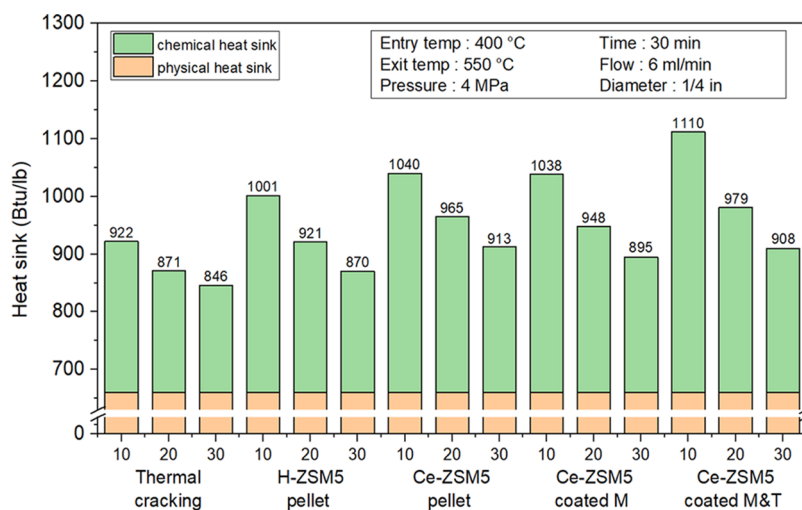
for 30 min. The catalysts modified with lanthanum and samarium showed slightly higher heat sinks than the H-ZSMS.

ZSMS that was modified with cerium had the highest initial heat sink of 1040 Btu/lb, which was maintained up to 900 Btu/lb after 30 min. The cerium-modified ZSMS catalyst had a higher heat sink and good activity retention than H-ZSMS, and the modification improved the performance of the ZSMS catalyst. Cerium-modified ZSMS exhibits excellent performance because the stability and activity of the catalyst improved with cerium doping. In addition, a high heat sink can be described as having a relatively high ratio of olefins between the gas and liquid products; more details are provided in Section 3.3.

By comparing the modified ZSMS catalysts, it was confirmed that the cerium-modified ZSMS catalyst was the most effective in improving the catalyst performance and thermal stability. The reaction characteristics of ZSMS catalysts coated on various supports were compared.

Figure 7 shows the heat sink for thermal cracking, the cerium-modified ZSMS pellet, and the catalyst coated with a metal foam and tube. The symbols M and T represent the metal foam and stainless steel tube, respectively. In all of the cases where a catalyst was used, it had a higher heat sink than thermal cracking. When cerium was coated on the metal foam during the reaction, the contact area increased; however, the heat sink decreased slightly compared with that of the pellet. It was inferred that the space velocity increased because of the space occupied by the metal foam inside the reactor, affecting the amount of heat sink.^{30,31} To address the decrease in the heat sink owing to the increase in space velocity, the amount of catalyst was increased via a metal foam and tube coating. When the reaction catalyst was coated with both metal foam and tube, the heat sink increased to 1100 Btu/lb, which is approximately 19% higher compared with thermal cracking. Thus, it was confirmed that the cerium-modified ZSMS exhibited excellent endothermic performance.

3.2.3. Coke Formation during the Decomposition Reaction. Coke is a carbon deposit that is produced during the reaction. The formation of coke not only reduces the mechanical strength of the reactor and prevents the channel of the reactor but also covers the surface of the catalysts to reduce their activity. Therefore, a decrease in the amount of coke was required at the time of the reaction. Figure 8 shows the amount of coke formed and the amount formed by comparing the

**Figure 7.** Heat sink of the endothermic reaction using the cerium-modified ZSMS catalyst.

weights of the catalyst, reactor tube, and filter before and after the reaction.

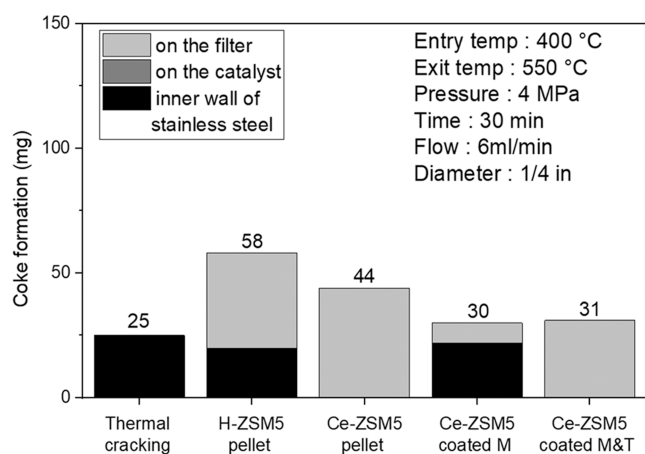


Figure 8. Coke formation during the decomposition reaction.

All of the catalytic reactions showed more coke formation than thermal cracking. Catalysts participate in the reaction, which promotes cracking and dehydrogenation reactions. Consequently, the proportion of olefin products increased, resulting in an increase in aromatic and diaromatic products. Aromatic and diaromatic compounds act as coke precursors, producing more coke than thermal cracking reactions. Because the use of catalysts promotes endothermic performance, excess coke formation can be adjusted simultaneously. Metals such as nickel and iron, components of tube and metal foam, promote the formation of filamentous coke. Filamentous coke is the main cause of coke generation in the inner wall. This causes serious problems for reactions such as blocking the inner wall of the reactor and damaging the inside of the reactor. When the cerium-modified catalyst was coated with metal foam and a tube, 31 mg of coke was produced on the filter. The amount of coke formed was lower than that formed by H-ZSM5. It is judged that the occurrence of coke was suppressed because the catalyst was coated on both the tube and metal foam to cover the metal material part, which is the generation site of the filamentous coke.

Figure 9 shows SEM images of the cerium-modified ZSM5-coated metal foam before and after the reaction. The scales of the SEM image are x50 (a and c) and x1000 (b and d). This confirmed that the pores of the catalyst support were not blocked after the reaction and that the shape of the catalyst was maintained. Table 4 summarizes the EDS results for the modified ZSM5-coated metal foam before and after the

Table 4. EDS Results of the Cerium-Modified ZSM5-Coated Metal Foam

cerium-modified ZSM5-coated metal foam		
element (atomic %)	before reaction	after reaction
C	0%	16.77%
Si	28.80%	22.39%
O	64.17%	54.89%
Ni	1.69%	1.52%
Fe	0.89%	0.72%
Al	2.42%	1.86%
Cr	2.10%	1.84%

reaction. The proportion of carbon increased, and the main components of ZSM5, Si, and O decreased. Ni, Fe, Al, and Cr were the components of the metal foam.

3.3. Product Analysis. **3.3.1. Thermally Stable Fuel Composition.** Figure 10 shows the analysis through GC-MS to confirm the composition of the thermally stable fuel before the catalysis reaction.

In the case of the thermally stable fuel, it is difficult to clearly indicate the specific composition ratio because the substances mixed. So it was classified according to the form of the compound. The thermally stable fuel consists of approximately 80% linear paraffin, 9% diaromatic, and 7% cyclo paraffin. Linear paraffin, which accounts for the largest proportion, is mainly composed of compounds such as decane, undecane, dodecane, tridecane, tetradecane, and dozens of other substances.

3.3.2. Gas Yield and Composition. The gas yield was calculated by the weight difference between the fuel's input and output over time. A sample of the gas products (0 min) was collected for 1 min immediately after the start of the reaction, and samples at 10, 20, and 30 min were collected from the gas products every 10 min. The composition ratios of the 11 types of gas products from CH₄ to C₄H₈ were analyzed using GC-FID.

Figure 11 shows the gas yield of thermal cracking, H-ZSM5 pellet, cerium-modified ZSM5 pellet, cerium-modified-ZSM5-coated M, and cerium-modified ZSM5-coated M&T reactions and the composition of gas products. The gas yield of 10–30 min has a high yield in the order of cerium-modified ZSM5-coated M&T, cerium-modified ZSM5 pellet, cerium-modified ZSM5-coated M, H-ZSM5 pellet, and thermal cracking. The gas yield and heat sink are not always proportional; however, the gas products increase the chemical heat sink.¹⁷ When the main component, n-dodecane, of the thermally stable fuel is converted to C₂H₄, the chemical heat sink is 1530 Btu/lb and has a high enthalpy value in the order C₂H₄ > C₃H₆ > cis-C₄H₈

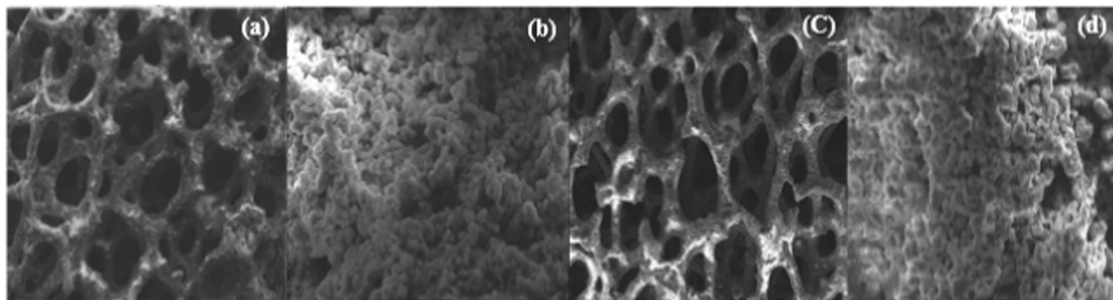


Figure 9. SEM images of the cerium-modified ZSM5-coated metal foam before the reaction (a, b) and after the reaction (c, d).

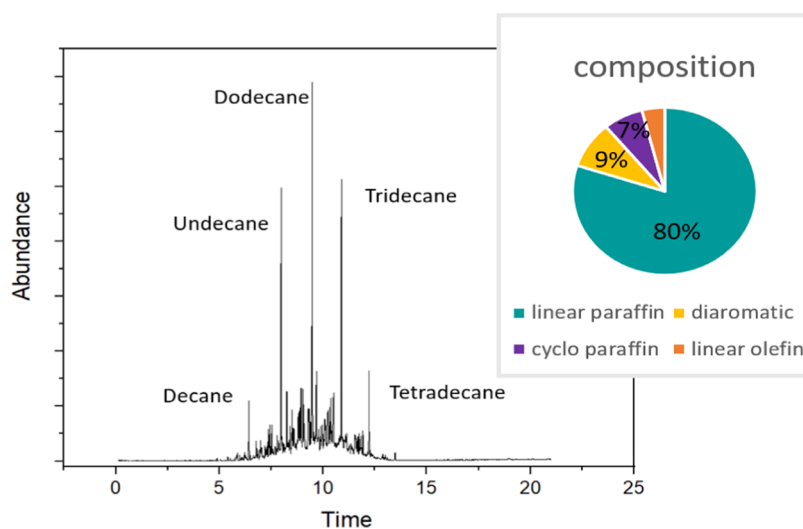


Figure 10. GC-MS analysis of a thermally stable fuel.

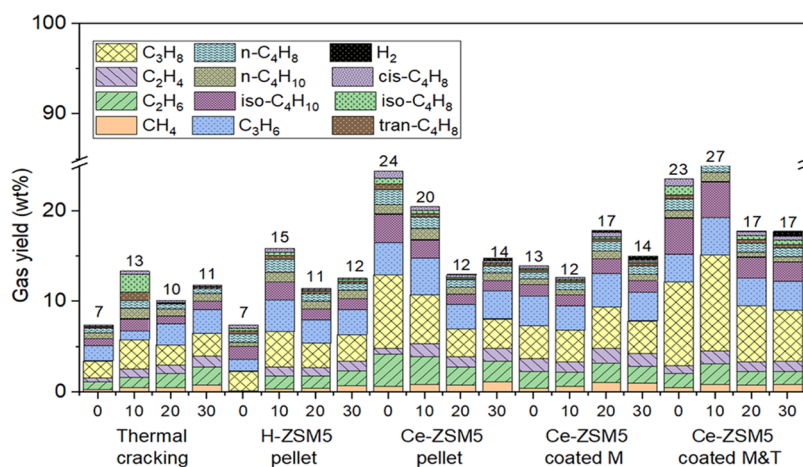


Figure 11. Gas yield and composition of the reaction using ceria-modified ZSM5 catalysts.

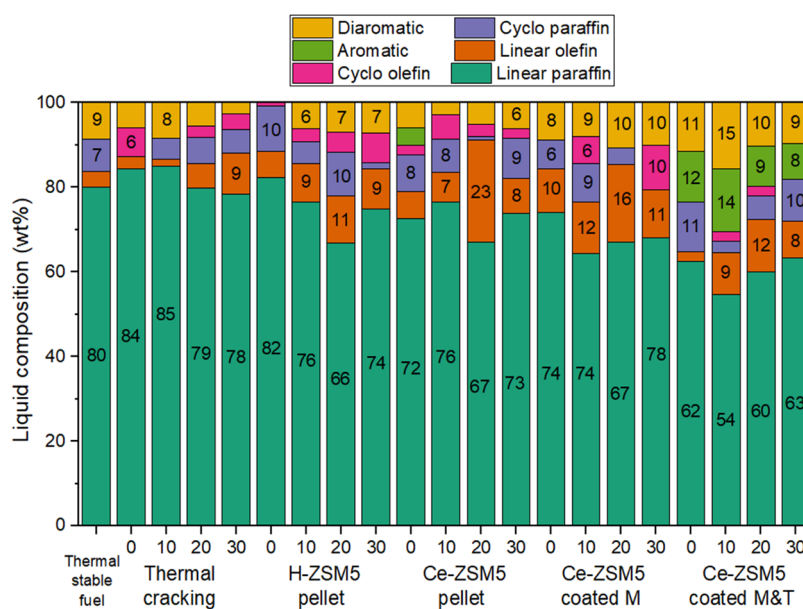


Figure 12. Liquid composition of reaction using the cerium-modified ZSM5 catalysts.

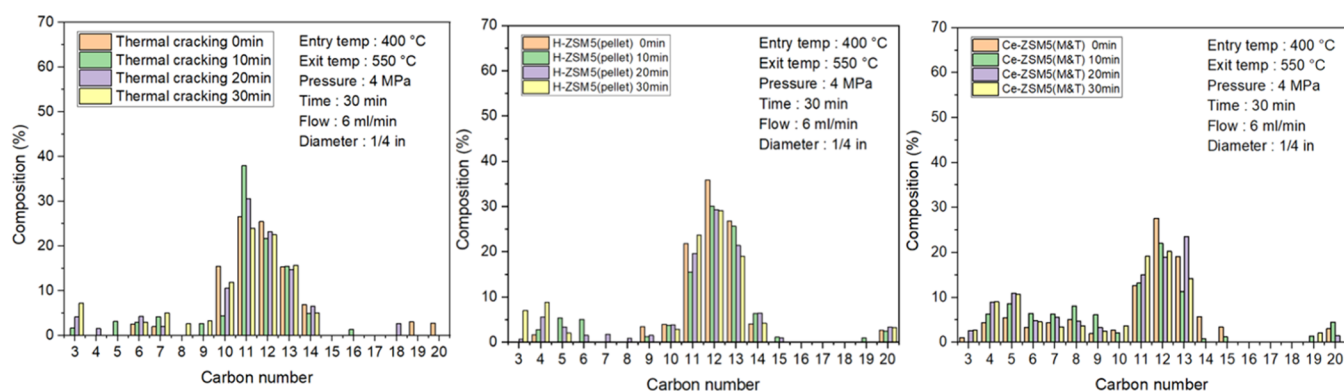


Figure 13. Carbon number of the liquid sample after the reaction.

> $n\text{-C}_4\text{H}_8$. In the case of cerium-modified ZSM5-coated M&T, catalyst reactions have been converted to the gas phase with wt % of 23, 27, 17, and 17%. The composition of C_2H_4 , C_3H_6 , and $\text{cis-C}_4\text{H}_8$, which have high enthalpy among the composition of gas products in 0 and 10 min, was 4.7% out of 23 and 6.2% out of 27%. Moreover, the use of a cerium-modified catalyst sample at 30 min has the highest ratio of hydrogen compared to the other reaction. In addition, the rate of olefin production and hydrogen generation ratio increased because the hydrogen transfer reaction was facilitated when modified with cerium and the dehydrogenation reaction was facilitated through nickel and iron components of the metal foam.

3.3.3. Liquid Product Composition. Samples of the liquid products were collected every 10 min at 0, 10, 20, and 30 min. The 0 min sample was obtained from the liquid products for 1 min immediately after the reaction. The liquid sample was analyzed over time using gas chromatography GC-MS. Figure 12 shows the composition of the liquid products of the thermally stable fuel after the reaction, which were thermal cracking, H-ZSM5 pellet, and the cerium-modified ZSM5 catalyst.

As a thermally stable fuel is a mixture of dozens of hydrocarbon compounds, it is difficult to accurately calculate the conversion rate. Therefore, we compared the compositions of the liquid products over time. When catalysts were used, the olefin and aromatic ratios increased compared with thermal cracking. In particular, the liquid composition of the cerium-modified ZSM5-coated M&T has an olefin ratio of approximately 10%, which is twice that of thermal cracking. In addition, the ratio of aromatics maintains at approximately 20% for 30 min in cerium-modified ZSM5-coated M&T and has a higher value than that in other reactions. Cerium modification caused a change of the acid sites. So, increasing the reaction contact area by coating with a cerium-modified catalyst promoted dehydrogenation and increased olefin and aromatic production. Olefins and aromatic products have high heat sinks. The high ratio of olefins to aromatics can explain why the coated support with the cerium-modified catalyst exhibited excellent endothermic performance and maintained a high heat sink until the end of the reaction.

Figure 13 is a classification of thermal cracking, H-ZSM5 pellet, and cerium-modified ZSM5-coated M&T according to the number of liquid products by carbon number. All three reactions showed an increase in the low molecular weight product over time; however, when using catalysts, the low molecular weight product ratio further increased over time. In particular, when using the cerium-modified ZSM5 catalyst, a

significant increase in the ratio of 4–8 products was observed with a carbon number comparable to that of the existing commercial catalyst H-ZSM5 from 10.8 to 22.5%. This means that the cerium-modified ZSM5 is suitable for the cracking reaction of the fuel.

4. CONCLUSIONS

Modification with lanthanum increases the activity of the catalyst. Thermally stable fuel decomposition was performed using ZSM5 catalysts prepared by doping lanthanum, cerium, and samarium, which have these characteristics. All three catalysts showed a higher amount of heat sink compared to conventional ZSM5. The highest heat sink was shown at 1100 Btu/lb in the cerium-modified ZSM5-coated M&T, which increased the heat sink about 10% compared to the conventional commercial catalyst H-ZSM5. This is because the ratio of olefins and aromatic products with a high heat sink in the composition of gas and liquid products increased relatively. The increase in the olefin and aromatic compositions was due to the cerium-modified catalyst's acid site and nickel and iron in the metal foam, which facilitated the dehydrogenation reaction. In addition, comparing the results of liquid products classified by carbon number, the ratio of low molecular weight products over time was higher when using cerium-modified ZSM5 than that of thermal cracking and the H-ZSM5 pellet. This indicates that cerium-modified ZSM5 is a suitable catalyst for both dehydrogenation and cracking reactions during the thermally stable fuel decomposition reaction.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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