

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



---

# Iron Oxide-Based Catalyst for Catalytic Cracking of Heavy Oil

---

Eri Fumoto, Shinya Sato and  
Toshimasa Takanohashi

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.72719>

---

## Abstract

This chapter describes an iron oxide catalyst containing Zr and Al for production of light hydrocarbons by catalytic cracking of petroleum residual oil in a steam atmosphere. The catalyst was hematite structure and useful for decomposition and desulfurization of residual oil. After lattice oxygen of iron oxide reacted with heavy oil fraction of residual oil, oxygen species generated from steam were supplied to iron oxide lattice and reacts with heavy oil fraction, producing light hydrocarbons and carbon dioxide. When the oxygen species were generated from steam, hydrogen species were simultaneously generated from steam. The hydrogen species were transferred to light hydrocarbons, hydrogen sulfide, and residue deposited on the catalyst. Supplies of the hydrogen species to light hydrocarbons suppressed alkene generation. Generation of hydrogen sulfide indicated decomposition of sulfur compounds of residual oil. The sulfur concentration of product oil decreased compared to the concentration of residual oil. Some oxygen species could be transferred to sulfur dioxide. Accordingly, hydrogenation and oxidation by the hydrogen and oxygen species derived from steam provided the decomposition and desulfurization of residual oil with the iron oxide-based catalyst in a steam atmosphere.

**Keywords:** iron oxide catalyst, atmospheric residue, steam catalytic cracking

---

## 1. Introduction

Petroleum refineries require production of transportation fuels by decomposition of petroleum residual oil. The residual oil has low H/C ratio, high viscosity, and impurities, such as sulfur, vanadium, and nickel. Hence, decomposition of the residual oil is not easy.

The conventional process to convert heavy oil, such as petroleum residual oil, to light hydrocarbons was coking, visbreaking, residue fluidized catalytic cracking (RFCC), and hydrocracking

[1, 2]. Heavy oil was decomposed with Ni-Mo or Co-Mo catalysts to produce light hydrocarbons with less coke under high hydrogen pressure in the hydrocracking process. The hydrocracking is a useful technique to produce light hydrocarbons, which has high H/C ratio, although hydrogen is expensive.

Steam can be an alternative hydrogen source for conversion of heavy oil to light hydrocarbons with catalysts. This technique requires the following catalyst properties: (i) a high ability to decompose heavy oil, (ii) stable activity under high steam temperature, and (iii) resistance to deposition of coke, sulfur, and metals. Iron oxide is not expensive and can be a candidate the catalyst to decompose heavy oil in a steam atmosphere.

This chapter describes an iron oxide-based catalyst for decomposition of heavy oil to produce light hydrocarbons. Properties of the catalyst and catalyst activity to decompose residual oil and desulfurization in a steam atmosphere are discussed.

## 2. Properties of iron oxide catalyst

Several studies reported the catalytic cracking of heavy oil with iron oxide catalysts. Fumoto et al. developed the  $\text{ZrO}_2$ -supporting  $\alpha\text{-Fe}_2\text{O}_3$  catalysts for oxidative cracking of petroleum residual oil under high steam temperature [3]. Hosseinpour et al. reported catalytic cracking of petroleum residual oil using silica-supported  $\alpha\text{-Fe}_2\text{O}_3$  nanoparticles under super critical water [4]. Nguyen-Huy and Shin studied steam catalytic cracking of petroleum residual oil using  $\text{ZrO}_2$ -impregnated macro-mesoporous red mud, which consisted of  $\alpha\text{-Fe}_2\text{O}_3$  and  $\text{TiO}_2$  [5]. Phase diagram of ferrite showed that  $\text{Fe}_2\text{O}_3$  is alloyed with  $\text{Al}_2\text{O}_3$  homogeneously [6]. Hence, Fumoto et al. modified the  $\text{ZrO}_2$ -supporting  $\alpha\text{-Fe}_2\text{O}_3$  catalysts by addition of Al to enhance the catalyst durability [7, 8]. We described the properties of the  $\alpha\text{-Fe}_2\text{O}_3$  catalysts containing Zr and Al in this section.

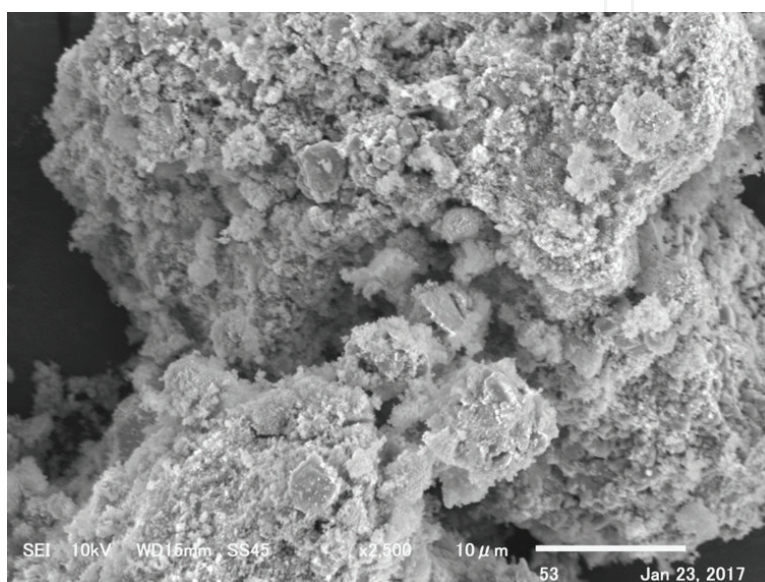
### 2.1. Preparation of $\alpha\text{-Fe}_2\text{O}_3$ catalyst containing Zr and Al

The  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al was prepared by a coprecipitation method using aqueous solution of  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$  (Special grade, Wako Pure Chemical Industries, Ltd., 146 mol/m<sup>3</sup>),  $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$  (Special grade, Wako Pure Chemical Industries, Ltd., 19 mol/m<sup>3</sup>), and  $\text{ZrOCl}_2 \cdot 8\text{H}_2\text{O}$  (Special grade, Wako Pure Chemical Industries, Ltd., 9 mol/m<sup>3</sup>) with aqueous ammonia [9, 10]. The catalyst was pelletized without binder, crushed, and sieved to obtain particles of 300–850  $\mu\text{m}$  after the treatment at 873 K for 1 h in a steam atmosphere. The atomic ratio of Fe, Zr, and Al in the catalyst was 1:0.06:0.13.

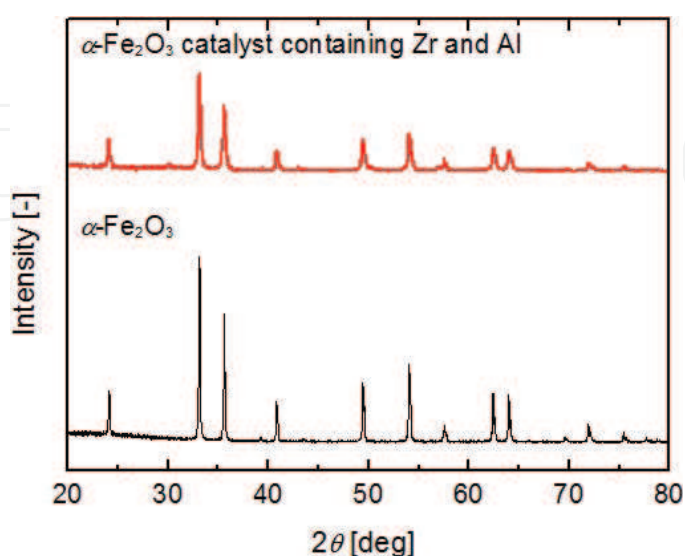
### 2.2. Structure of $\alpha\text{-Fe}_2\text{O}_3$ catalyst containing Zr and Al

The morphology of the  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al was analyzed by scanning electron microscope (SEM, JSM-6010LA, JEOL Ltd.). **Figure 1** showed a SEM image of  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al prepared by a coprecipitation method. The catalyst was composed of randomly shaped particles.

The crystalline construction of the catalyst was analyzed by X-ray diffraction (XRD, M03XHF22, Mac Science Co. Ltd.). **Figure 2** showed the XRD patterns of the catalyst and reagent iron (III) oxide ( $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>, first grade, Wako Pure Chemical Industries, Ltd.) [9]. The patterns of the catalyst corresponded to that of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>. Absence of peaks corresponding to ZrO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> indicates high dispersion of Al and Zr in the  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> matrix [7]. The peaks of the catalyst are broader compared to the reagent iron oxide, indicating that the domain size of the  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> lattice was small. The catalyst containing Zr and Al showed smaller domain size than the ZrO<sub>2</sub>-supporting  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> catalyst without Al, and the small domain size positively affected the catalyst durability [7, 8].



**Figure 1.** SEM image of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> catalyst containing Zr and Al.



**Figure 2.** XRD patterns of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> catalyst containing Zr and Al and reagent  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> (reproduced from elsewhere [9]).

### 3. Activity of $\alpha\text{-Fe}_2\text{O}_3$ catalyst containing Zr and Al for decomposition of heavy oil

The  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al was used for catalytic cracking of atmospheric residual oil (AR) derived from Middle East crude [9]. **Table 1** showed the properties of AR [11]. Composition of light oil (boiling point <623 K), vacuum gas oil (VGO, boiling point 623–773 K), and vacuum residue (VR, boiling point >773 K) was determined by the gas chromatographic distillation (HP6890, Agilent Technologies) with a wide-bore capillary column according to ASTM D 2887. AR has high viscosity, low H/C ratio, and high content of high-boiling-point components. This section describes the activity of the catalyst to decompose AR in a steam atmosphere.

#### 3.1. Decomposition of AR

Catalytic cracking of AR was conducted using a downflow-type fixed-bed reactor loaded with 1.5 g of catalyst at 748 K under atmospheric pressure [9, 12]. A 10 wt% solution of AR with toluene was fed to the reactor at flow rate ( $F$ ) of 1.1 g/h using a syringe pump. AR was diluted with toluene to reduce the viscosity of AR, and the catalyst was confirmed to be

	AR
<b>Composition [wt%]</b>	
Light oil	7
VGO	49
VR	44
Density [g/cm <sup>3</sup> ]	0.944
<b>Elemental analysis [wt%]</b>	
C	85.7
H	11.6
N	0.16
S	2.48
H/C [mol/mol]	1.63
<b>Conradson carbon residue [wt%]</b>	5.8
<b>Metals [ppm]</b>	
V	10
Ni	4
Fe	10
Reproduced from elsewhere [11].	

**Table 1.** Properties of AR.

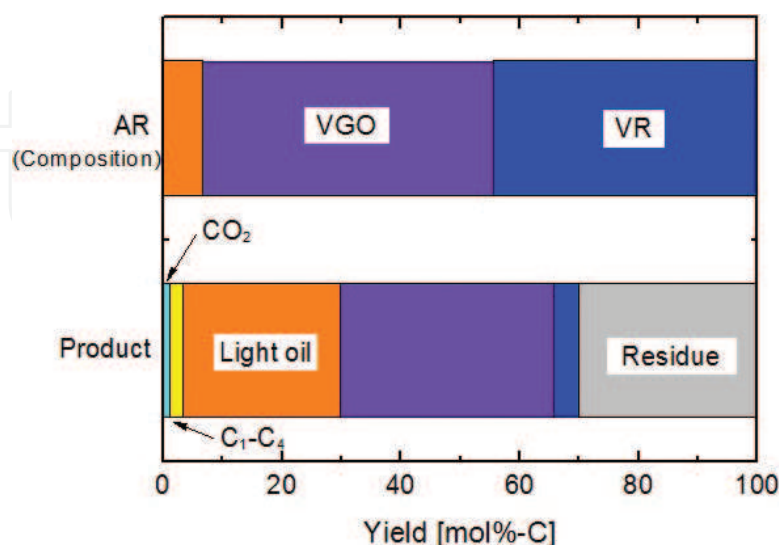


almost inactive to toluene. Total flow rate of mixture of steam and nitrogen was adjusted to 80 cm<sup>3</sup>(STP)/min. After 2 h of operation, the pump of AR solution was stopped, and the reactor was cooled. The gas products were separated through an ice trap and analyzed by gas chromatography (GC-12A and GC-14A, Shimadzu Corp.) with thermal conductivity and flame ionization detectors equipped with Porapak-Q and Unibeads 3S columns, respectively. The boiling point distribution was determined by the gas chromatographic distillation. The residue deposited on the catalyst was analyzed by elemental analysis (EA1110, Finningan Mat).

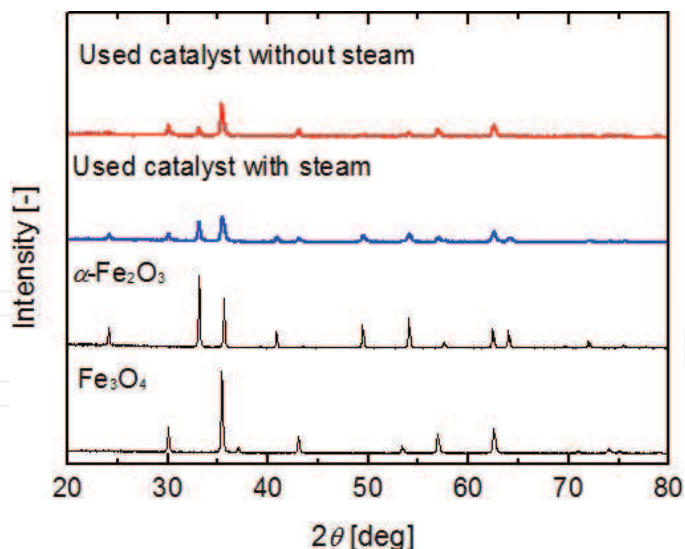
**Figure 3** showed the composition of AR and product yield of the AR cracking at flow rate ratio of steam to AR solution ( $F_s/F$ ) of 0.42 g/g [9]. The high-boiling-point components, such as VGO and VR, decreased, producing light oil, CO<sub>2</sub>, organic gas (C<sub>1</sub>–C<sub>4</sub>), and residue. Generation of CO<sub>2</sub> indicated that the heavy oil fraction was oxidatively cracked.

**Figure 4** showed the XRD patterns of the used catalysts after the catalytic cracking of AR with and without steam [9]. The patterns of reagent iron (III) oxide ( $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) and iron (II, III) oxide (Fe<sub>3</sub>O<sub>4</sub>, Strem Chemicals, Inc.) were shown for comparison. The patterns of both used catalysts consisted of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> and Fe<sub>3</sub>O<sub>4</sub>. The peaks of Fe<sub>3</sub>O<sub>4</sub> mainly appeared in the patterns of the used catalyst without steam. These results indicated that part of lattice oxygen of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> reacted with heavy oil fractions to produce light hydrocarbons and CO<sub>2</sub> at first [12]. Then, oxygen species generated from steam were incorporated into the iron oxide lattice and reacted with heavy oil fractions. Hence, the  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> structure was partially maintained after the reaction with steam. Consequently, the heavy oil fractions were oxidatively cracked using oxygen species derived from steam.

When dodecylbenzene was used as a model compound of heavy oil, a small amount of oxygen containing compounds, such as phenol, acetophenone, undecanone, and hydroxybiphenyl, was produced in the catalytic cracking of dodecylbenzene [9]. Kondoh et al. reported that the catalytic cracking of heavy oil with heavy oxygenated water (H<sub>2</sub><sup>18</sup>O) produced CO<sub>2</sub> containing



**Figure 3.** Product yield of catalytic cracking of AR with steam ( $F_s/F = 0.42$ ) and composition of AR (reproduced from elsewhere [9]).



**Figure 4.** XRD patterns of used catalysts for catalytic cracking of AR with and without steam ( $F_s/F = 0, 0.42$ ), reagent  $\alpha$ - $\text{Fe}_2\text{O}_3$ , and reagent  $\text{Fe}_3\text{O}_4$  (reproduced from elsewhere [9]).

heavy oxygen ( $\text{CO}^{18}\text{O}$ ) [13]. Accordingly, most of oxygen species were supplied to form  $\text{CO}_2$ , and a small amount of oxygen species was supplied to oxygen-containing compounds.

The  $\alpha$ - $\text{Fe}_2\text{O}_3$  catalyst containing Zr showed the higher activity than the  $\alpha$ - $\text{Fe}_2\text{O}_3$  catalyst without Zr because  $\text{ZrO}_2$  in the catalyst promotes the generation of oxygen species from steam [3]. Addition of Al to the catalyst enhanced the durability of the catalyst. The activity of the  $\text{ZrO}_2$ -supporting  $\alpha$ - $\text{Fe}_2\text{O}_3$  catalyst without Al decreased after the sequence of reaction and regeneration because of phase change of iron oxide and subsequent peeling of  $\text{ZrO}_2$  [7].

### 3.2. Effect of steam on product of AR cracking

To examine the effect of steam flow rate on product yield of AR cracking, catalytic cracking of AR was conducted at various steam flow rates ( $F_s/F = 0\text{--}3.0$ ), and the product yield was shown in **Figure 5** [9]. The yields of light oil, VGO, VR, and residue little changed, suggesting that steam concentration hardly affected the decomposition of heavy oil. The heavy oil fractions reacted with oxygen species incorporated from steam to the iron oxide lattice after the lattice oxygen of  $\alpha$ - $\text{Fe}_2\text{O}_3$  reacted with heavy oil fractions. The  $\text{CO}_2$  yield increased with increase in the flow rate ratio of steam to AR solution due to increase in oxygen species derived from steam.

When oxygen species were generated from steam and reacted with heavy oil, hydrogen species were simultaneously generated from steam [9]. Consumed amount of steam was calculated from the  $\text{CO}_2$  yield in the catalytic cracking of AR at flow rate ratio of steam to AR solution ( $F_s/F$ ) of 3.0 g/g and shown in **Figure 6**. If half of the sulfur compounds in AR were converted to  $\text{H}_2\text{S}$  by the reaction of hydrogen species and sulfur compounds, approximately 14% of hydrogen species were supplied to form  $\text{H}_2\text{S}$ . Approximately 19% of hydrogen species

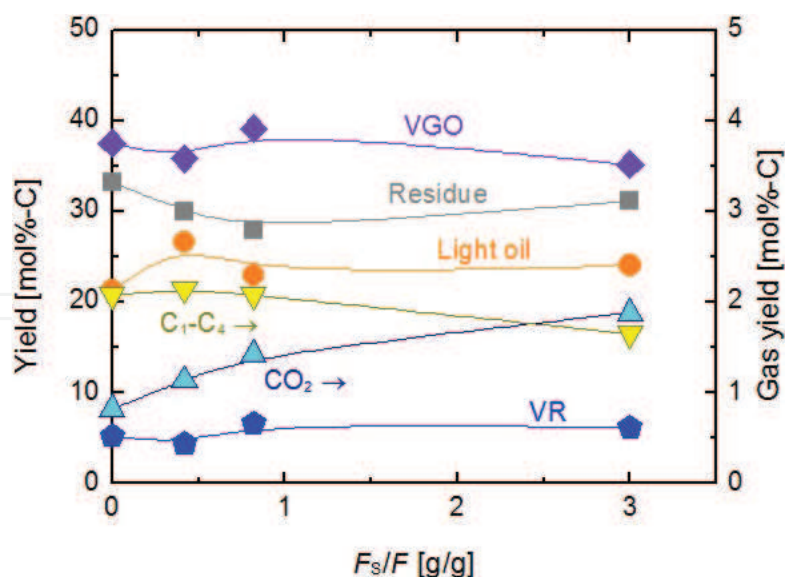


Figure 5. Product yield of catalytic cracking of AR with and without steam ( $F_s/F = 0-3.0$ ) (reproduced from elsewhere [9]).

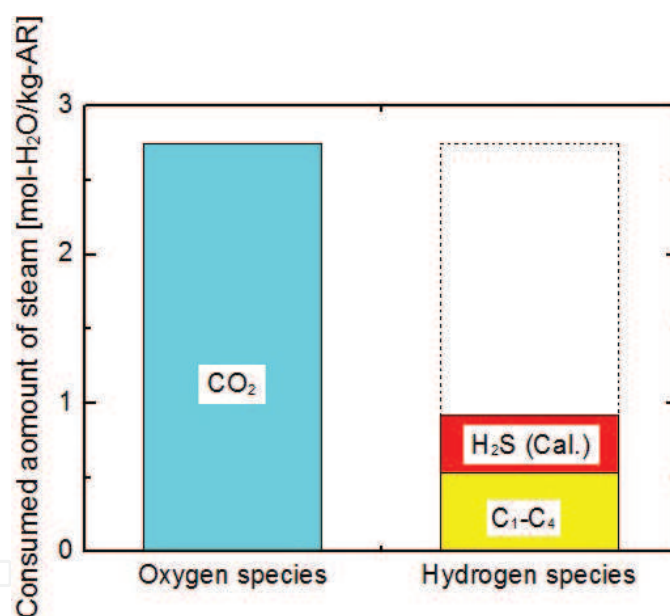
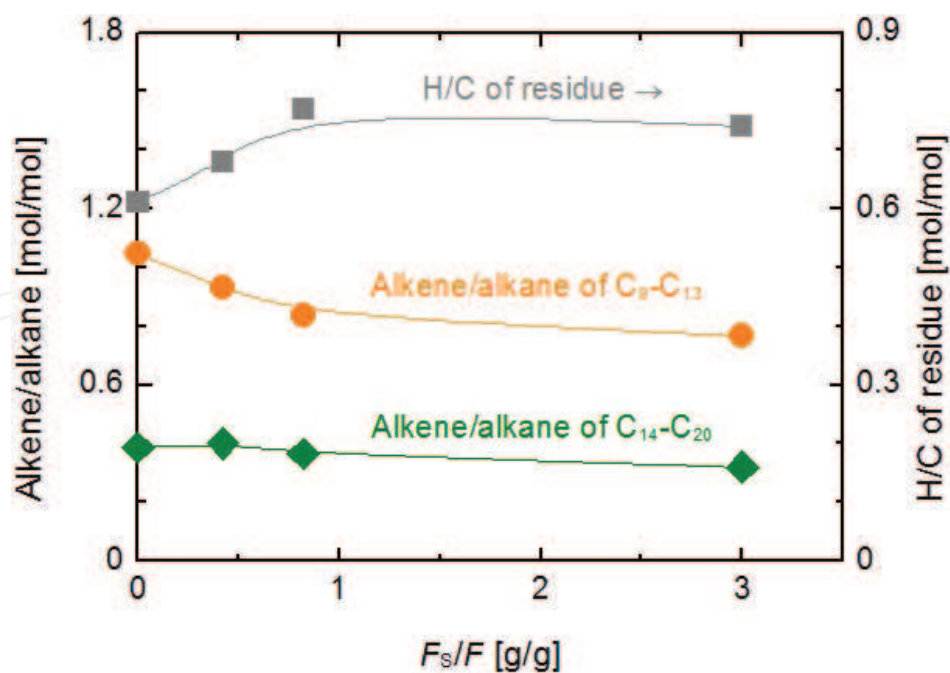


Figure 6. Consumed amount of steam for catalytic cracking of AR with steam ( $F_s/F = 3.0$ ).

were supplied to form  $C_1-C_4$  hydrocarbons if two moles of hydrogen species were supplied to 1 mole of  $C_1-C_4$  hydrocarbons. Hence, the remaining hydrogen species (approximately 67%) might be supplied to liquid hydrocarbons and residue.

Supplies of hydrogen species from steam to liquid hydrocarbons and residue resulted in decrease in alkene generation and increase in H/C of residue [9]. Figure 7 showed the alkene/alkane ratio of aliphatic hydrocarbons and H/C ratio of residue produced by the catalytic cracking of AR with and without steam. The aliphatic hydrocarbons in the liquid





**Figure 7.** Alkene/alkane ratio of aliphatic hydrocarbons and H/C ratio of residue produced by the catalytic cracking of AR with and without steam ( $F_s/F = 0-3.0$ ) (reproduced from elsewhere [9]).

product were analyzed by gas chromatography with a flame ionization detector (GC-FID, 6890N, Agilent Technologies) and mass spectrometry (GC-MS, HP6890-HP5973, Agilent Technologies) with capillary columns. The alkene/alkane ratio of light hydrocarbons ( $C_9-C_{13}$ ) decreased with increase in flow rate ratio of steam to AR solution, suggesting that hydrogen transfer from steam to light hydrocarbons suppressed alkene generation. The H/C ratio of residue produced by the AR cracking with steam was higher than that produced by the AR cracking without steam. Some hydrogen species supplied from steam to the residue and others supplied to light hydrocarbons.

#### 4. Activity of $\alpha\text{-Fe}_2\text{O}_3$ catalyst containing Zr and Al for desulfurization of heavy oil

The petroleum residual oil including AR contains sulfur. Hydrodesulfurization is the useful method to remove sulfur from petroleum, producing high-quality oil. The residual oil contains acyclic sulfur compounds, such as thiols and disulfides, and cyclic compounds including thiophene ring. The decomposition of the cyclic sulfur compounds was harder than acyclic compounds [14].

The catalytic cracking of heavy oil with steam using the  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al produced the hydrogen species during the reaction of heavy oil with the oxygen species derived from steam [9]. Some hydrogen species were supplied to hydrocarbons and residue. The remaining hydrogen species might react with sulfur compounds in AR and be supplied to form  $\text{H}_2\text{S}$  [10]. Hence, desulfurization of AR with the catalyst in a steam atmosphere was examined in this section.

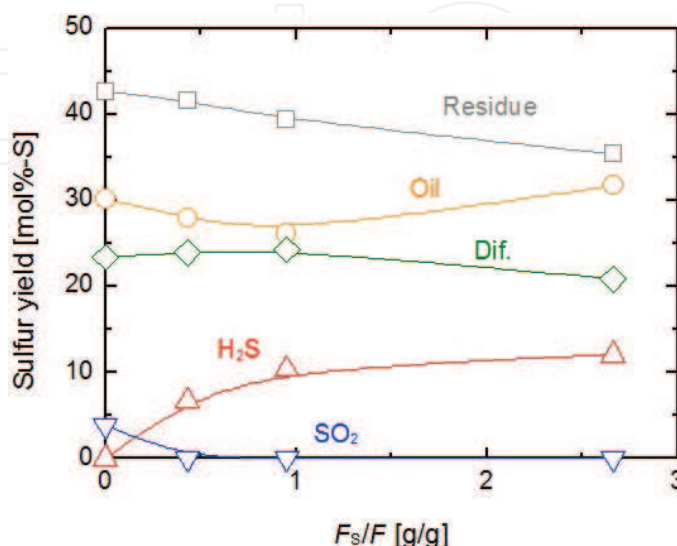
#### 4.1. Desulfurization of AR

Catalytic cracking of AR with the  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al was conducted in a steam atmosphere ( $F_s/F = 2.7$ ) [10]. The reaction conditions were the same as decomposition of AR at 3.1. Produced amounts of  $\text{H}_2\text{S}$  and  $\text{SO}_2$  were measured by gas detecting tube (GASTEC Corp.). Sulfur content in liquid products was determined by oxidative microcoulometry according to JIS K 2541-2. Sulfur contents deposited on the catalyst were measured by elemental analysis (EA1110, Finningan Mat.)

Catalytic cracking of AR produced approximately 61 mol%-C of oil product, 4 mol%-C of gas product, and 35 mol%-C of residue. Sulfur concentration in the product oil decreased to 1.4 wt% compared to the 2.5 wt% of sulfur in AR, and  $\text{H}_2\text{S}$  was generated, indicating that sulfur compounds in AR were decomposed [10]. When desulfurization was conducted using dibenzothiophene as a model compound of a cyclic sulfur compound in AR, dibenzothiophene was decomposed producing  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , hydrocarbons, and sulfur compounds [10]. Hence, acyclic and cyclic sulfur compounds might be decomposed with the catalyst in a steam atmosphere.

#### 4.2. Effect of steam on desulfurization of AR

To examine the effect of steam on desulfurization of AR, catalytic cracking of AR was conducted at various steam flow rates ( $F_s/F = 0\text{--}2.7$ ) [10]. **Figure 8** showed the sulfur yield of catalytic cracking of AR at flow rate ratio of steam to AR solution ( $F_s/F$ ) of 0–2.7. The carbon yield of oil and residue was almost constant as shown in **Figure 5**. The catalytic cracking of AR without steam produced little  $\text{H}_2\text{S}$ , and the  $\text{H}_2\text{S}$  yield increased with increase in flow rate ratio of steam to AR solution. The  $\text{CO}_2$  yield also increases with increase in the flow rate ratio of steam to AR solution. These results indicated that sulfur compounds reacted with some hydrogen species derived from steam to produce  $\text{H}_2\text{S}$  when oxygen species reacted with heavy oil.



**Figure 8.** Sulfur yield of catalytic cracking of AR with and without steam ( $F_s/F = 0\text{--}2.7$ ) (reproduced from elsewhere [10]).

The  $\text{SO}_2$  was detected only in the reaction without steam. The lattice oxygen of iron oxide reacted with sulfur compounds, producing  $\text{SO}_2$  in the catalytic cracking of AR without steam. The  $\text{SO}_2$  has high solubility in water (1.4 mol/kg at 25°C [15]). Hence, no  $\text{SO}_2$  might be detected in the catalytic cracking of AR with steam, even if oxygen species generated from steam reacted with sulfur compounds to form  $\text{SO}_2$ . Some  $\text{H}_2\text{S}$  produced in the reaction also could be dissolved in water. When nitrogen was injected into the water collected in this reaction,  $\text{H}_2\text{S}$  was detected [10]. The difference was approximately 23 mol%-S because of sulfur content, such as  $\text{H}_2\text{S}$  and  $\text{SO}_2$ , in water and measurement errors of sulfur concentration.

Sulfur content in residue decreased with increase in flow rate ratio of steam to AR solution. Larger amounts of hydrogen species were generated at higher ratio of steam to AR solution and reacted with heavy sulfur compounds deposited on the catalyst to produce light sulfur compounds and  $\text{H}_2\text{S}$ . Sulfur concentration in the oil decreased because sulfur compounds were decomposed to produce  $\text{H}_2\text{S}$ . Increase in sulfur concentration in the oil at  $F_g/F = 2.7$  was resulted from production of light sulfur compounds by the reaction of heavy sulfur compounds with large amounts of oxygen and hydrogen species.

## 5. Conclusion

Decomposition and desulfurization of AR were examined using  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al in a steam atmosphere. The catalyst was prepared by coprecipitation method. Heavy oil fraction of AR was decomposed with the catalyst, producing  $\text{CO}_2$ , light hydrocarbons, and residue. The lattice oxygen of  $\alpha\text{-Fe}_2\text{O}_3$  reacted with heavy oil at first. Then, oxygen species generated from steam were supplied to the iron oxide lattice and react with heavy oil fraction, producing light hydrocarbons and  $\text{CO}_2$ . Hydrogen species generated from steam during the reaction of the oxygen species, and heavy oil fraction supplied to light hydrocarbons,  $\text{H}_2\text{S}$ , and residue. Supplies of the hydrogen species to light hydrocarbons suppressed alkene generation. Some hydrogen species reacted with sulfur compound of AR, producing  $\text{H}_2\text{S}$ . Some  $\text{SO}_2$  could be generated by the reaction of sulfur compound and oxygen species derived from steam. Consequently, hydrogen species and oxygen species derived from steam reacted with heavy oil fraction and sulfur compound of AR with the  $\alpha\text{-Fe}_2\text{O}_3$  catalyst containing Zr and Al in a steam atmosphere to produce light hydrocarbons.

## Acknowledgements

This work was partially supported by Grants-in-Aid for Young Scientist B (21760622, 23760733) and Scientific Research C (25420822) from the Japan Society for the Promotion of Science (JSPS).

## Author details

Eri Fumoto\*, Shinya Sato and Toshimasa Takanohashi

\*Address all correspondence to: e-fumoto@aist.go.jp

Research Institute of Energy Frontier, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan

## References

- [1] Moulijn JA, Makkee M, Van Diepen A. Chemical Process Technology. Hoboken, NJ: John Wiley & Sons, Ltd; 2001. pp. 32-78
- [2] Sahu R, Song BJ, Im JS, Jeon YP, Lee CW. A review of recent advances in catalytic hydrocracking of heavy residues. *Journal of Industrial and Engineering Chemistry*. 2015;**27**:12-24
- [3] Fumoto E, Tago T, Tsuji T, Masuda T. Recovery of useful hydrocarbons from petroleum residual oil by catalytic cracking with steam over zirconia-supporting iron oxide catalyst. *Energy & Fuels*. 2004;**18**:1770-1774
- [4] Hosseinpour M, Ahmadi SJ, Fatemi S. Successive co-operation of supercritical water and silica-supported iron oxide nanoparticles in upgrading of heavy petroleum residue: Suppression of coke deposition over catalyst. *The Journal of Supercritical Fluids*. 2015;**100**:70-78
- [5] Nguyen-Huy C, Shin E. Amelioration of catalytic activity in steam catalytic cracking of vacuum residue with ZrO<sub>2</sub>-impregnated macro-mesoporous red mud. *Fuel*. 2016;**179**:17-24
- [6] Kubaschewski O, Schmid-Fetzer R, Petzow G, Effenberg G, editors. Ternary Alloys. Vol. 5. Weinheim, Germany: VCH; 1992. p. 334
- [7] Fumoto E, Tago T, Masuda T. Production of lighter fuels by cracking petroleum residual oils with steam over zirconia-supporting iron oxide catalysts. *Energy & Fuels*. 2005;**20**:1-6
- [8] Fumoto E, Tago T, Masuda T. Recovery of lighter fuels from petroleum residual oil by oxidative cracking with steam over Zr-Al-FeO<sub>x</sub> catalyst. *Chemistry Letters*. 2006;**35**:998-999
- [9] Fumoto E, Sugimoto Y, Sato S, Takanohashi T. Catalytic cracking of heavy oil with iron oxide-based catalysts using hydrogen and oxygen species from steam. *Journal of the Japan Petroleum Institute*. 2015;**58**:329-335
- [10] Fumoto E, Sato S, Takanohashi T. Desulfurization of heavy oil with iron oxide-based catalysts using steam. *Journal of the Japan Petroleum Institute*. 2015;**58**:336-340

- [11] Fumoto E, Sato S, Takanohashi T. Catalytic cracking of heavy oil over a complex metal oxide catalyst in a steam atmosphere. In: Dalai AK, editor. *Nanocatalysis for Fuels and Chemicals*. Washington, DC: American Chemical Society; 2012. pp. 75-85
- [12] Fumoto E, Matsumura A, Sato S, Takanohashi T. Recovery of lighter fuels by cracking heavy oil with Zirconia–Alumina–Iron Oxide catalysts in a steam atmosphere. *Energy & Fuels*. 2009;**23**:1338-1341
- [13] Kondoh H, Hasegawa N, Yoshikawa T, Nakasaka Y, Tago T, Masuda T. Effects of H<sub>2</sub>O addition on oil sand bitumen cracking using a CeO<sub>2</sub>–ZrO<sub>2</sub>–Al<sub>2</sub>O<sub>3</sub>–FeOx catalyst. *Energy & Fuels*. 2016;**30**:10358-10364
- [14] Mochida I, Choi K. An overview of hydrodesulfurization and hydrodenitrogenation. *Journal of the Japan Petroleum Institute*. 2004;**47**:145-163
- [15] National Institute of Standards and Technology. NIST Chemistry WebBook [Internet]. Available from: <http://webbook.nist.gov/chemistry/>