



Evaluation of hydrogen transfer in FCC catalysts. A new approach for cyclohexene as a test reactant

Gabriela de la Puente, Ulises Sedran*

Instituto de Investigaciones en Catálisis y Petroquímica, INCAPE (FIQ, UNL - CONICET), Santiago del Estero 2654, 3000 Santa Fe, Argentina

Received 10 November 1998; accepted 5 May 1999

Abstract

The conversion of cyclohexene over different commercial FCC catalysts in a batch fluidized-bed reactor under very short contact times at 300°C, was described by means of a simple lumped kinetic model that accounted for the observed yield patterns. The main branch of reaction starting from the adsorption of cyclohexene was used to assess an index based on kinetic parameters that defines the relative significance of hydrogen transfer reactions in a set that also includes proton transfer and cracking reactions. Complementary experiments with pulses of reactant on a fixed-bed reactor allowed to establish the best temperature to obtain maximum sensitivity to hydrogen transfer. The same evolutions were observed for the relationships between the index of hydrogen transfer and the paired acid site density with the Y zeolite unit cell size, confirming that two regions can be defined separated by unit cell sizes of about 24.28–24.30 Å, the correlations being stronger at low values of this parameter. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Hydrogen transfer; FCC; Cyclohexene; Y zeolite

1. Introduction

Hydrogen transfer reactions are considered to play a very important role among the large number of very complex reactions that occur in the process of catalytic cracking of hydrocarbons (FCC), since they have a strong incidence on both product distributions and catalyst stability (Scherzer, 1989). In effect, the classic overall descriptive statement about the reaction between olefins and naphthenics to yield paraffins and aromatics has been used to explain the differences in the product slates observed in the shift from amorphous to crystalline catalysts in gas oil cracking (more aromatics and paraffins in the case of zeolite catalysts), as well as its consequences on product quality, mainly on gasoline octanes (Scherzer, 1989; Biswas & Maxwell, 1990). Although both intra and intermolecular hydrogen transfers are possible, the main focus about these reactions in relation to FCC has been on intermolecular processes, like the model interaction between olefins and naphthenes, that was confirmed to be feasible (Parra, Goldwasser, Fajula & Figueras, 1985).

The degree of dealumination of the zeolitic component in the compound FCC catalysts (the Y zeolite) has an important impact on the hydrogen transfer: the more dealuminated the zeolite, the less extended the reaction. Although some discrepancies exist about the reaction mechanisms, it is clear that for a given zeolite type, the density of paired acid sites is an important governing parameter (Peters, Cheng & Roberie, 1992; Sedran, 1994), yet it has also been postulated that the controlling issue is the catalyst affinity for olefin adsorption (Corma, Faraldos & Mifsud, 1989). In general, it is accepted that a carbenium ion adsorbed on the catalyst surface takes an hydride ion from a nearby donor molecule — this defines the reaction as bimolecular, to desorb saturated, while the donor, which adsorbs as a carbenium ion, may repeat the process, desorb dehydrogenated after donating a proton back to the catalyst, or suffer β -cracking to yield an olefin and a smaller carbenium ion on the surface (Corma, Mocholi, Orchillés, Koermer & Madon, 1991).

Due to the importance of these reactions in FCC, a number of indexes has been used to estimate their extent when cracking usual feedstocks, or to qualify the associated catalyst properties. Those indexes usually refer to the relationship between the yields of paraffins and

* Corresponding author. Tel.: 00-54-42-528062; fax: 00-54-42-531068.
E-mail address: usedran@fiqus.unl.edu.ar (U. Sedran)

olefins in given hydrocarbon cuts (Hayward & Winkler, 1990; Bonetto, Corma & Herrero, 1992), or just yields are considered (Habib, 1990; Guerzoni & Abbot, 1993). The focus being on gasoline product quality, a correlation is observed between gasoline octanes, the properties of the zeolitic component, and hydrogen transfer: the higher the unit cell size, the more intense the hydrogen transfer and the lower the octanes, mainly due to the consumption of olefins. However, more specific assessments could be performed by means of test reactions. Naphthene and olefin compounds have a good potential as probe molecules, since in the case of naphthenes they can donate hydride ions, thus originating resonance-stabilized carbenium ions, while olefins are strong hydride ion acceptors once they are protonated. Methylcyclohexane (Corma et al., 1991) and methylcyclopentane (de la Puente & Sedran, 1996) were used following different quantitative approaches. Particularly, cyclohexene may play a dual role as a donor or acceptor of hydride ions. Its conversion was used under different experimental conditions and evaluation approaches, e.g. the evolution of initial selectivities (Magnoux, Gallet & Guisnet, 1987; Cheng & Rajagopalan, 1989; Dwyer, Karim & Ojo, 1991), the yields of various products (Jacquinot et al., 1990, Mercier des Rochettes, Marcilly, Gueguen & Bousquet, 1990), or the values of the kinetic constants in lumped models (Suarez, Cheng, Rajagopalan & Peters, 1990). Other cyclic olefins, like cyclopentene (Mercier des Rochettes et al., 1990) or methylcyclohexene (Corma et al., 1991) were also used.

It is the objective of this work to develop a new, optimized approach for the conversion of cyclohexene as a tool for the evaluation of hydrogen transfer reactions over different FCC catalysts, and to study their relation with zeolite properties, with the particular utilization of commercial catalysts and a batch, fluidized-bed reactor under very short contact times.

2. Experimental

Commercial FCC catalysts were used, their properties being summarized in Table 1. Equilibrated samples ECAT-E (conventional catalyst) and ECAT-O (octane

catalyst) were obtained from running refineries, while the others catalysts were dealuminated by steaming in the laboratory in a fluidized-bed reactor with 100% steam following conventional procedures. Catalysts A-1 and G are conventional, and P is a fresh ultrastable research catalyst. A steamed, low alumina silica–alumina amorphous catalyst (sample KT-4) was also used. The physical properties of the catalysts were determined by means of nitrogen adsorption isotherms and conventional techniques. The zeolite unit cell sizes were determined by means of the ASTM D-3942-85 standard method.

The experiments were performed in a batch, internal recirculation fluidized-bed reactor named Riser Simulator, which mimics the conditions of commercial FCC units, and that was specifically designed to perform studies in relation to FCC. The isothermal laboratory reactor unit has been described thoroughly elsewhere (de Lasa, 1992; Sedran, 1994). Runs were performed under short contact times between 1.5 and 12 s, the mass of catalyst being 0.8 g and the amount of reactant injected 0.2 ml. Cyclohexene (Fluka, min. 99%) was used without further purification. The reaction temperature (300°C) was decided after tuning experiments performed with a pulse technique on a fixed-bed reactor under the following conditions: nitrogen carrier gas, 130 ml/min; reactant pulse volume, 3 µl; reaction temperatures between 200 and 400°C, and the mass of catalyst was changed according to catalyst activity in order to get similar conversions. Catalysts A-1 (60 mg), ECAT-E (100 mg) and KT-4 (170 mg) were used in the pulse experiments. In both types of experiments (fixed- and fluidized-bed reactors), the reaction products were analyzed by on-line gas chromatography, using a 60 m long, 0.25 mm i.d., methylsilicone capillary column. The mass balances in the experiments closed to more than 96% in all the cases.

The values of the kinetic parameters were assessed through a conventional, least-squares Marquardt-type optimization method.

3. Results and discussion

The most favorable temperature in order to obtain maximum sensitivity towards hydrogen transfer reactions

Table 1
Properties of the catalysts used

Catalyst	Specific surface area (m ² g ⁻¹)	Zeolite content (wt%)	Zeolite unit cell size (Å)	Rare-earth oxides content (wt%)
P	344	21.6	24.54	0.00
A-1	230	17.3	24.41	1.31
ECAT-E	147	11.5	24.29	1.42
G	213	21.4	24.28	n.a.
ECAT-O	151	15.9	24.24	0.00
KT-4	147	—	—	—

Table 2
Product selectivities (%) as a function of temperature. Pulse experiments on catalyst ECAT-E

ECAT-E						A-1	KT-4	
Temp. (°C)	Conv. (%)	C6 ⁻	MCPE	DIM	MCPA	MCPA/(MCPA + MCPE + C6 ⁻)	MCPA/(MCPA + MCPE + C6 ⁻)	MCPA/(MCPA + MCPE + C6 ⁻)
200	18.9	0.00	6.41	79.4	1.6	0.193	—	—
250	29.3	0.00	15.2	58.0	7.4	0.329	—	—
300	55.5	0.41	14.9	41.7	23.0	0.600	0.650	0.138
350	69.5	0.85	22.6	33.7	27.9	0.544	—	—
400	87.8	2.26	23.9	25.6	31.8	0.505	—	—

was selected by means of experiments with a pulse technique on a fixed-bed reactor. Zeolite-containing catalysts A-1 and ECAT-E, and amorphous catalyst KT-4 were used. The most important products of cyclohexene (CHE) conversion in these experiments were methylcyclopentane (MCPA), methylcyclopentenes (MCPE), cyclohexane (CHA), dimeric products (DIM), and minor amounts of compounds with six or less carbon atoms per molecule (C6⁻) and methylcyclohexane (MCHA). As an example, the product distributions obtained with catalyst ECAT-E at the various temperatures are presented in Table 2 in terms of selectivities (product yields divided by conversion). It can be appreciated that the relative significances of the various products change as a function of temperature. It will be shown later that the relationship that can be established between the yield of MCPA and the combined yields of MCPA, MCPE and cracking products (C6⁻), is a proper index to describe the relative importance of hydrogen transfer reactions. This relationship exhibits a maximum value when the reaction temperature is 300°C, in coincidence with other results (Magnoux et al., 1987), which was selected for the additional experiments. It can also be seen that the value of this relationship decreases in the order A-1 > ECAT-E > KT-4, suggesting that the intensity of hydrogen transfer follows the same order, as expected between zeolitic and amorphous catalysts, and also corresponding to the unit cell sizes of the zeolitic ones (refer to Table 1).

The experiments performed with the internal recirculation, fluidized-bed reactor at short contact times allowed to observe the same reaction products, and to determine the yield curves (yield versus conversion) for each of them. Since the conversions were lower and the contact between catalyst and reactants very different, cyclohexadienes (C6DIE) were now observed quantitatively. The corresponding yield curves of the most important products are presented in Fig. 1 for the case example of catalyst G. It is to be stressed that the qualitative behavior on the other catalysts was the same, differences being

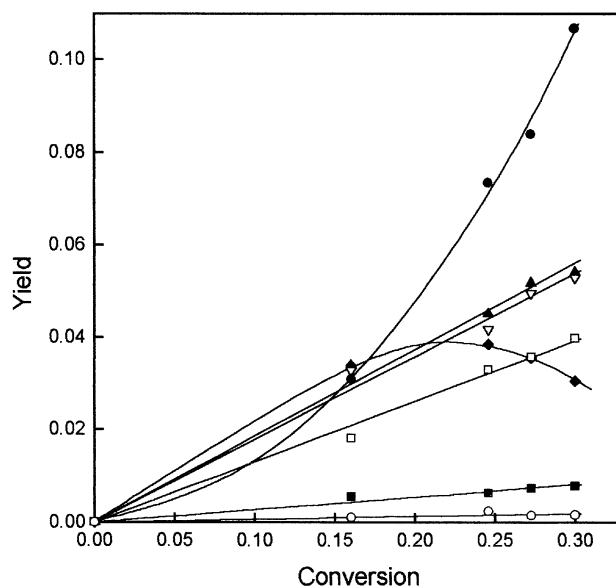
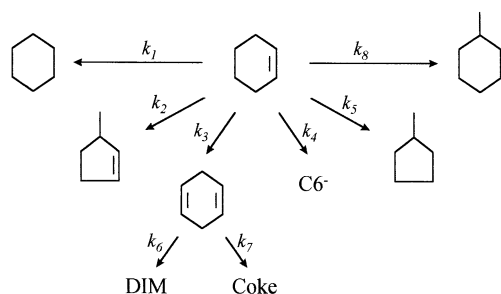


Fig. 1. Product yields as a function of conversion for catalyst G. Batch fluidized-bed reactor, T: 300°C. Symbols: MCPA, (▲); MCPE, (□); CHA, (▽); DIM, (●); C6DIE, (◆); C6⁻, (○); MCHA, (■).

observed on the quantitative performances according to the catalysts properties, as it will be discussed later. Then, according to their yield curves, reaction products can be classified in the following way: MCPA, MCPE, CHA and C6⁻ are stable primary, and C6DIE are unstable primary. Although DIM could be classified as primary plus secondary stable products, they show a behavior that correspond essentially to stable secondary products, and will be considered in consequence; this characteristic is more pronounced on other catalysts. Methylcyclohexane (MCHA) is formed in low amounts and its yield curves correspond to a stable primary product, although it is obvious that steps with addition of a carbon atom, or oligomerization — cracking, are necessary; since this product is present even at low conversions, it will be considered a primary product. It is to be noted that some



Scheme 1. Reaction scheme for cyclohexene conversion. Overall lumped kinetic model.

differences with the classifications performed by Cheng and Rajagopalan (1989), who used a flow fixed-bed reactor, are observed.

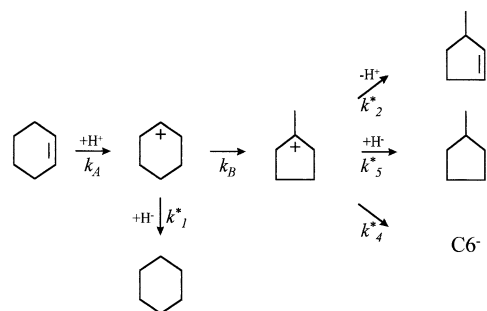
After these considerations, it is possible to draw the simple kinetic model that is shown in Reaction Scheme 1 where, due to the low conversions achieved, all the reactions are considered to be of pseudo-first order. The assumption of first order for the reaction of hydrogen transfer is also backed by the following facts (Mercier des Rochettes et al., 1990): the high partial pressure of reactant CHE, the high affinity of olefins for the acid sites and the fast isomerization rate of adsorbed cyclohexyl to methylcyclohexyl ion. Then the individual rate equations and the mass balances for each system component in the batch reactor can be written as

$$r_i = k_{i0} y_j \exp(-\gamma_i t),$$

$$-\frac{dy_j}{dt} = \sum_i \xi_{j,i} r_i,$$

where k_{i0} is the initial value of the kinetic constant for reaction i according to Reaction Scheme 1, y_j represents the mass fraction of component j , $\xi_{j,i}$ is a coefficient (0, 1 or -1) accounting for the role of component j in reaction i , γ_i is the corresponding deactivation parameter in the exponential deactivation functions (α , for reactions 1 to 5 and 8, or β , for reactions 6 and 7) and t is the reaction time. The kinetic constants also include some system parameters, like the masses of catalyst and reactant, that were kept unaltered for all the experiments.

It is clear at this point that, considering the products obtained, the conversion of cyclohexene is a test reaction that at least reveals the following simultaneous reactions occurring on these acidic catalysts: isomerization (as denoted by the yield of MCPE), oligomerization (as indicated by DIM compounds), and cracking (as shown by C_6^- products). Saturated products with the same carbon atom number as the reactant, that is, CHA and MCPA, could point to the occurrence of hydrogen transfer reactions and, e.g., CHA could be considered a product of direct hydrogen transfer from donor molecules to adsorbed cyclohexyl carbenium ions formed from the protonation of reactant cyclohexene molecules. However, an



Scheme 2. Main branch of reaction for cyclohexene conversion.

adsorbed cyclohexyl ion could also be subjected to fast isomerization into the more stable methylcyclopentyl ion (Corma et al., 1991) which, in turn, may be exposed to different reactions: (i) a hydride transfer process analogous to the one previously described for cyclohexyl ions, to yield MCPA, (ii) ring opening and additional cracking to yield products with six or less carbon atoms, and (iii) transfer of a proton back to the catalyst surface to yield MCPE (refer to Reaction Scheme 2). According to the observed distribution of products, this is the most important branch of reaction. As a consequence of the fact that the assessment of the relative importance of the reactions that occur simultaneously in a given reacting system can be performed on a sounder basis if they proceed on the same adsorbed species, we prefer to relate the hydrogen transfer process to exclusively the set of reactions on methylcyclopentyl ions. Then, the index i_{HT} to quantify hydrogen transfer will be defined for each catalyst as the ratio between the corresponding kinetic constants for hydride transfer and the addition of those of proton transfer, cracking and hydride transfer on this ion; the ratio can be shown to be equivalent to the one that can be written using the analogous k_i constants, i.e.:

$$i_{HT} = \frac{k_2^*}{(k_2^* + k_4^* + k_5^*)} = \frac{k_{50}}{(k_{20} + k_{40} + k_{50})}$$

The fitting of the experimental data to this model and the subsequent regression of kinetic parameters allow to predict product yields as a function of reaction time. In that sense, it has to be considered that the singular reaction environment and the complete lack of temperature and concentration gradients outside the catalyst particles (Pekediz, Kraemer, Chabot & de Lasa, 1992) confer additional confidence to the data gathered. The example of Fig. 2 for catalyst G shows the adequacy of the model, but it is to be stressed that the same quality of response was appreciated on the other catalysts. Table 3 summarizes the values of the kinetic parameters (deactivation parameters and initial values of kinetic constants) for the various catalysts. Kinetic parameters were estimated with 95% confidence intervals (not shown for the sake of clarity) that, in the average, were less than

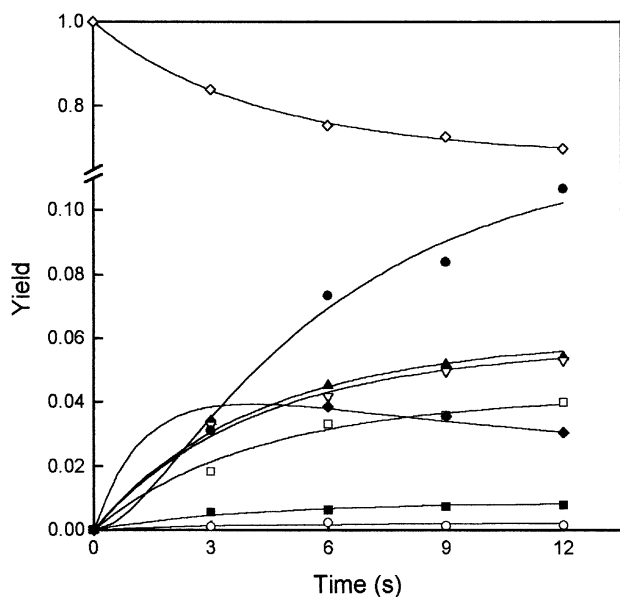


Fig. 2. Product yields as a function of reaction time for catalyst G. Batch fluidized-bed reactor, T: 300°C. Symbols as in Fig. 1; CHE, (\diamond).

20% of the value of the constants. The comparison of catalyst activities based on the initial values of the kinetic constants is not valid since, considering that it can be accepted that the activity in this type of catalysts is essentially due to the zeolite component, the zeolite content is different on each catalyst and, moreover, this component has different intrinsic activities, because the amount and degree of isolation of the acid sites is different as it can be deduced from the various unit cell sizes. However, it is possible to formulate relative comparisons. Concerning catalyst deactivation, it is to be noted that a different behavior was observed between the majority of reactions and those leading to coke and dimeric compounds; in effect, the deactivation process is slower in the latter reactions, as it can be appreciated in the com-

parison of the values of the corresponding parameters α and β .

According to the proposed dependency of the hydrogen transfer reactions on the density of paired acid sites (Peters et al., 1992; Sedran, 1994; Galiano & Sedran, 1997), and discarding structural effects since the zeolite is the same on all the catalysts, the values of the i_{HT} index are presented in Fig. 3 as a function of unit cell size. As mentioned, this parameter is an indirect evidence of the average number of aluminum atoms (and associated acid sites) that are present in the zeolite structure (Jorik, 1993); also the distribution of sites according to their neighborhood — the NNN next-nearest-neighbor concept — has been modeled in consequence (Pine, Maher & Wachter, 1984; Peters, Cheng, Shatlock, Wormsbecher & Habib,

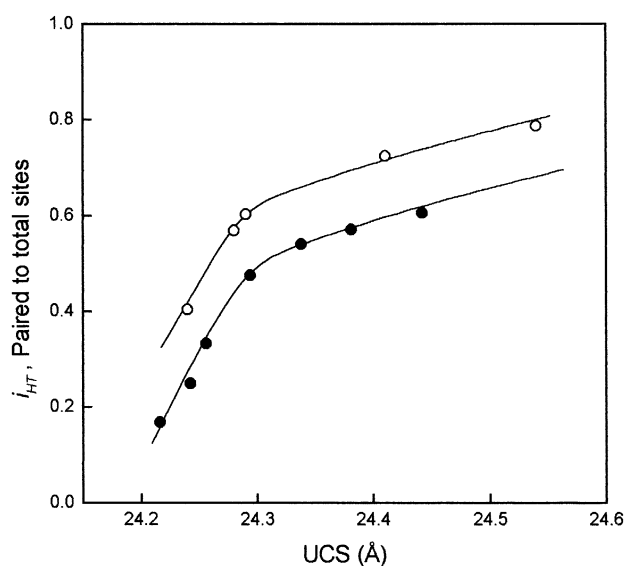


Fig. 3. Index i_{HT} (\circ) and ratio between the number of paired and total sites (\bullet) (calculated from the distribution model by Peters et al., 1990) as a function of zeolite unit cell size.

Table 3
Initial values of the kinetic constants, deactivation parameters and index i_{HT} for the various catalysts

Kinetic parameters (s^{-1})	Catalysts					
	P	A-1	ECAT-E	G	ECAT-O	KT-4
k_{00}	0.1443	0.0894	0.0675	0.0790	0.0650	0.0550
k_{10}	0.0230	0.0131	0.0086	0.0143	0.0076	0.0029
k_{20}	0.0013	0.0104	0.0106	0.0104	0.0131	0.0178
k_{30}	0.0322	0.0358	0.0287	0.0366	0.0343	0.0181
k_{40}	0.0162	0.0003	0.0007	0.0006	0.0001	0.0002
k_{50}	0.0681	0.0285	0.0172	0.0149	0.0090	0.0158
k_{60}	0.0748	0.0993	0.2957	0.5578	0.0961	0.1995
k_{70}	0.3626	0.0565	0.0052	0.0279	0.0171	0.0341
α	0.3383	0.2204	0.1409	0.2037	0.2166	0.1264
β	0.2304	0.0000	0.0000	0.1437	0.0000	0.0000
i_{HT}	0.796	0.726	0.603	0.574	0.404	0.468

1990). It can be observed that the lower the zeolite unit cell size, the lower the index values, with a steeper variation under a value of about 24.28–24.30 Å; this particular value for the shift in the slope of the rate of change of the index i_{HT} had also been observed with other test reactants (Sedran, 1994), and also linked to variations in the octane number of gasolines from the catalytic cracking of gas oil feedstocks (Cheng & Rajagopalan, 1989). A sharp increase in the olefin content of gasoline fractions was also observed for unit cell sizes below 24.30 Å (Peters et al., 1992).

This singular phenomenon can be associated to the fact that a strong decrease in the relative number of paired (1-NNN) aluminum sites for unit cell sizes under approximately 24.30 Å is to be expected, as predicted by site distribution models (Pine et al., 1984; Peters et al., 1990). In effect, the ratio between the number of paired and total sites, calculated from the distribution model by Peters et al. (1990) is also presented in Fig. 3 to notice that its behavior is fully analogous to the one of the index i_{HT} . It is to be noted that the correlations are independent of the type of catalyst used. This dependency of hydrogen transfer upon zeolite dealumination was also linked to the reduced capacity for olefin adsorption (Corma et al., 1989).

It is also apparent that the relative importance of the process of returning a proton back to the catalytic surface from the adsorbed carbenium ion to yield olefinic products (i.e. the value of the relationship $k_2^*/(k_2^* + k_4^* + k_3^*)$) shows a behavior inverse to that of i_{HT} .

4. Conclusions

Results from the conversion of cyclohexene over commercial FCC catalysts with different properties in a batch, fluidized-bed reactor run at very short reaction times can be analyzed with more confidence, based on the main branch of reaction that includes the isomerization of the adsorbed cyclohexene molecules into methylcyclopentyl ions; these ions can be further subjected to hydride transfer, proton transfer and cracking reactions. Data fitting to a suitable, simple lumped kinetic model which takes the conversion patterns into account produces the corresponding kinetic parameters. Thus, it is possible to define an index to account for the relative importance of hydrogen transfer reactions within the set of reactions affecting the same reactant, that correlates strongly with the zeolite unit cell size. It was confirmed that a sharp decrease in the extent of hydrogen transfer reactions will result below unit cell sizes of about 24.28–24.30 Å, in strong association with the change of the relative theoretical amount of paired acid sites in the zeolite. This procedure is free from masking effects like activity profiles along reactor beds.

References

- Biswas, J., & Maxwell, I. E. (1990). Recent process and catalyst-related development in FCC. *Applied Catalysis*, 63, 197–258.
- Bonetto, L., Corma, A., & Herrero, H. (1992). Beta zeolite as catalyst or catalyst additive for the production of olefins during cracking of gasoil. Paper presented at ninth international zeolite conference, Montreal, Canada, July 5–10.
- Cheng, W. -C., & Rajagopalan, K. (1989). Conversion of cyclohexene over Y-zeolites: A model reaction for hydrogen transfer. *Journal of Catalysis*, 119, 354–358.
- Corma, A., Faraldos, V., & Mifsud, A. (1989). Influence of the level of dealumination on the selective adsorption of olefins and paraffins and its implication on hydrogen transfer reactions during catalytic cracking on USY zeolites. *Applied Catalysis*, 47, 125–133.
- Corma, A., Mocholí, F., Orchillés, V., Koermer, G. S., & Madon, R. J. (1991). Methylcyclohexane and methylcyclohexene cracking over zeolite Y catalysts. *Applied Catalysis*, 67, 307–324.
- de la Puente, G., & Sedran, U. (1996). Conversion of methylcyclopentane on rare earth exchanged Y zeolite FCC catalysts. *Applied Catalysis A: General*, 144, 147–158.
- de Lasa, H. I. (1992). U.S. Patent 5,102,628.
- Dwyer, J., Karim, K., & Ojo, A. (1991). Bimolecular hydrogen transfer over zeolites and SAPOs having the faujasite structure. *Journal of Chemical Society Faraday Transactions*, 87, 783–786.
- Galiano, M. C., & Sedran, U. (1997). Light alkene selectivity on Y zeolite FCC catalysts. *Industrial Engineering and Chemical Research*, 36, 4207–4211.
- Guerzoni, F. N., & Abbot, J. (1993). Catalytic cracking of a hydrocarbon mixture on combination of HY and HZSM-5 zeolites. *Journal of Catalysis*, 139, 289–303.
- Habib, E. T. Jr. (1990). The effect of catalyst feedstock and operating conditions on the composition and octane number of FCC gasoline. In H. J. Lovink & L. A. Pine. *The hydrocarbon chemistry of FCC naphtha formation*. Proceedings of the symposium on Division of petroleum chemistry, ACS, September 10–15, 1989, Miami, FL (p. 1) Paris: Technip.
- Hayward, C. M. T., & Winkler, W. S. (1990). FCC: Matrix/zeolite interactions. Interaction of matrix and zeolite plays a role to determine the results from catalyst in FCC. *Hydrocarbon Processing*, February, 55–56.
- Jacquino, E., Mendes, A., Raatz, F., Marcilly, C., Ribeiro, F. R., & Caeiro, J. (1990). Catalytic properties in cyclohexane transformation of modified HY zeolites. *Applied Catalysis*, 60, 101–117.
- Jorik, V. (1993). Semiempirical approach to determination of framework aluminium content in faujasite-type zeolites by X-ray powder diffraction. *Zeolites*, 13, 187–191.
- Magnoux, P., Gallet, A., & Guisnet, M. (1987). Formation de coke, désactivation et régénération des zéolithes. IV — Transfert d'hydrogène et formation de coke au cours de la transformation du cyclohexène sur une zéolithe USHY. Influence de la température de réaction. *Bulletin of the Chemical Society of France*, 5, 810–814.
- Mercier des Rochettes, B., Marcilly, C., Gueguen, C., & Bousquet, J. (1990). Kinetic study of hydrogen transfer of olefins under catalytic cracking conditions. *Applied Catalysis*, 58, 35–52.
- Parra, C. F., Goldwasser, M. R., Fajula, F., & Figueras, F. (1985). A study of the TH reaction between isobutene and cyclohexane over zeolites using C-13 labelled molecules. *Applied Catalysis*, 17, 217–222.
- Pekediz, A., Kraemer, D. W., Chabot, J., de Lasa, H. I. (1992). Mixing patterns in a novel riser simulator. In H. I. de Lasa, G. Dogu, A. Ravella, *Chemical reactor technology for environmentally safe reactors and products*, vol. 225 (pp. 133–146). NATO ASI Series E. Dordrecht: Kluwer.

- Peters, A. W., Cheng, W. C., Shatlock, M., Wormsbecher, R. F., & Habib Jr., E. T. (1990). The structural elements of faujasite and their impact on cracking selectivity. In D. Barthomeuf, E. G. Derouane, & W. Holderich, *Guidelines for mastering the properties of molecular sieves* (pp. 365–372). New York: Plenum Press.
- Peters, A. W., Cheng, W.-C., & Roberie, T. G. (1992). Scientific aspects of novel catalysts for FCC. In H. I. de Lasa, G. Dogu, A. Ravella, *Chemical reactor technology for environmentally safe reactors and products*, vol. 225 (pp. 51–69). NATO ASI Series E. Dordrecht: Kluwer.
- Pine, L. A., Maher, P. J., & Wachter, W. A. (1984). Prediction of cracking catalyst behavior by a zeolite unit cell size mode. *Journal of Catalysis*, 85, 466–476.
- Scherzer, J. (1989). Octane-enhancing, zeolitic FCC catalysts: scientific and technical aspects. *Catalysis Review Science and Engineering*, 31, 215–354.
- Sedran, U. (1994). Laboratory testing of FCC catalysts and hydrogen transfer properties evaluation. *Catalysis Review Science and Engineering*, 36, 405–432.
- Suarez, W., Cheng, W. -C., Rajagopalan, K., & Peters, A. W. (1990). Estimation of hydrogen transfer rates over zeolite catalysts. *Chemical Engineering Science*, 45, 2581–2588.