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Title	REACTION STRUCTURE OF ETHYLENE HYDROGENATION ON METALLIC CATALYSTS : Part 4. Analysis with Reaction of Equimolar d ₀ - and d ₄ -ethylene with Equimolar Hydrogen and Deuterium
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Citation	JOURNAL OF THE RESEARCH INSTITUTE FOR CATALYSIS HOKKAIDO UNIVERSITY, 23(1), 17-25
Issue Date	1976-01
Doc URL	https://hdl.handle.net/2115/24986
Type	departmental bulletin paper
File Information	23(1)_P17-25.pdf



REACTION STRUCTURE OF ETHYLENE HYDROGENATION ON METALLIC CATALYSTS

Part 4. Analysis with Reaction of Equimolar d₀- and d₄-ethylene with Equimolar Hydrogen and Deuterium

By

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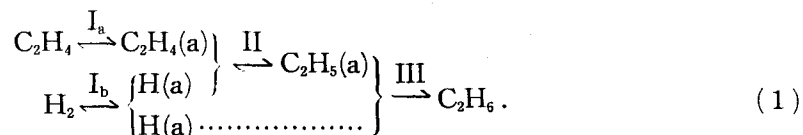
(Received February 3, 1975)

Abstract

A new method is proposed for evaluation of the rates of elementary steps in ethylene hydrogenation over metallic catalysts. This method is based on analysis of the evolution rates of d₁-, d₂-ethylene and d₁-hydrogen in course of the reaction of equimolar d₀- and d₄-ethylene with equimolar hydrogen and deuterium. The results of analysis with the reaction over evaporated Cu, Rh, Ni and Pt films show that the method is advantageous in a case of ethylene hydrogenation accompanying a fast isotopic mixing of hydrogen in ethylene.

Introduction

Rates of the following elementary steps I_a *etc.* in deuteration of light ethylene over various metal catalysts have been evaluated in previous works.¹⁻⁶⁾



In these works the rates of steps are given as functions of two parameters, *i.e.*, the deuterium fractions of adsorbed ethylene and adsorbed hydrogen atoms, which are evaluated from the evolution rates of deuterio-substituted ethylene, hydrogen and ethane measured at the initial stage of ethylene deuteration. This method, however, has a disadvantage that usual mass-

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spectrometric measurement of the amounts of deuterio-ethanes is inevitably so inaccurate as to give a considerable error in evaluation of the rates of steps. Method of the mass-spectrometric measurement has been improved^{3,7,8)} but not sufficiently reliable. It is consequently advisable to develop a new method for evaluation of the rates of steps without measuring the evolution rates of deuterio-ethanes.

When an equimolar mixture of d_0 - and d_4 -ethylene reacts with an equimolar mixture of hydrogen and deuterium, the parameters mentioned above are constantly 0.5 with neglect of isotopic effect, and the rates of steps I_a and II of scheme (1) can be evaluated from the rate of hydrogen mixing in ethylene as developed in the present paper, while the rate of step I_b has been shown^{2,3)} to be evaluated from the rate of isotopic equilibration of hydrogen and deuterium during the reaction. As a matter of course, this method is not applicable to a case where hydrogen mixing in ethylene or hydrogen proceeds on sites inactive for ethylene hydrogenation as concluded with Co oxide catalyst⁹⁾ or *via* any steps other than the steps of scheme (1), *e.g.*, dissociative adsorption of ethylene as observed with freshly evaporated Ni film.^{2,10)}

The present method is applied to the reaction over evaporated Cu, Rh, Ni and Pt films and the results are discussed in comparison with the previous results.¹⁻³⁾

Calculation of Rates of Elementary Steps

Symbols used are summarized below.

- V_s : steady rate of ethylene hydrogenation,
 $v_+(s), v_-(s)$: forward or backward unidirectional rate of step s ,
 P, D, H : protium, deuterium or hydrogen atom (irrespective of P or D),
 $V^{E_l}, V^{H_m}, V^{A_n}$: evolution rate of d_l -ethylene (E_l), d_m -hydrogen (H_m) or d_n -ethane (A_n),
 X_l, x_l : fraction of d_l -ethylene in gas or adsorbed phase,
 Y_m, Z_n : fraction of d_m -hydrogen in H_2 or d_n -ethane in C_2H_6 ,
 y_1, y_0 : fraction of D(a) or P(a) in H(a),
 P_E, P_H : partial pressure of ethylene or hydrogen.

Evolution rates of deuterio-substituted ethylene, hydrogen and ethane are given according to scheme (1) as

$$V^{E_l} = x_l v_-(I_a) - X_l v_+(I_a), \quad (l=0, \dots, 4), \quad (2)$$

$$V^{H_m} = \frac{2!}{(2-m)!m!} y_0^{2-m} y_1^m v_-(I_b) - Y_m v_+(I_b), \quad (m=0, 1, 2), \quad (3)$$

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and

$$V^{\Lambda n} = (y_0^2 x_n + 2y_0 y_1 x_{n-1} + y_1^2 x_{n-2}) v_+ \text{(III)}, \quad (n=0, \dots, 6), \quad (4)$$

respectively, where isotopic effect is ignored and the term including $v_- \text{(III)}$ is neglected in Eq. (4) as step III is perfectly irreversible under usual experimental conditions.¹⁰⁾ Steady rate of ethylene hydrogenation is given as

$$V_s \equiv -dP_E/dt = v_+(s) - v_-(s), \quad (s=I_a, I_b, II \text{ or III}). \quad (5)$$

Steady state condition for adsorbed d_1 -ethylene is given as^{*)}

$$\begin{bmatrix} b_0 & c_0 & 0 & 0 & 0 \\ a_1 & b_1 & c_1 & 0 & 0 \\ 0 & a_2 & b_2 & c_2 & 0 \\ 0 & 0 & a_3 & b_3 & c_3 \\ 0 & 0 & 0 & a_4 & b_4 \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} X_0 \\ X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix}, \quad (6)$$

where

$$\left. \begin{aligned} a_i &= (l-5) y_1 v_- \text{(II)} / 6v_+ \text{(I}_a\text{)}, \\ b_i &= 1 + (4y_1 - ly_1 + ly_0) v_- \text{(II)} / 6v_+ \text{(I}_a\text{)}, \\ c_i &= -(l+1) y_0 v_- \text{(II)} / 6v_+ \text{(I}_a\text{)}. \end{aligned} \right\} \quad (7)$$

On the other hand, V^{E_i} is expressed in terms of X_i and P_E as

$$V^{E_i} \equiv \frac{d(X_i P_E)}{dt} = \frac{dX_i}{dt} P_E + \frac{dP_E}{dt} X_i. \quad (8)$$

Eliminating V^{E_i} and $v_+ \text{(I}_a\text{)}$ from Eqs. (2), (5) and (8), we have

$$dX_i/dt = -(X_i - x_i) v_- \text{(I}_a\text{)} / P_E \quad (9)$$

and, further,

$$\frac{dX_i}{dt} = -\left(X_i - \sum_{l=1}^5 \frac{M_{i,l+1}}{M} X_{l-1} \right) \frac{v_- \text{(I}_a\text{)}}{P_E} \quad (10)$$

by substitution of x_l from Eq. (6). In Eq. (10), M is the coefficient matrix of x_l in the left side of Eq. (6) and $M_{i,l+1}$ is the cofactor of $(i, l+1)$ element of M .

The following relations hold throughout the reaction of equimolar d_0 - and d_1 -ethylene with equimolar P_2 and D_2 , with neglect of isotopic effect:

$$y_1 = y_0 = 0.5, \quad (11)$$

*) Cf. ref. 4, p. 178 or ref. 10, p. 44.

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$$X_0 = X_4, X_1 = X_3, X_2 = 1 - 2(X_0 + X_1), \quad (12)$$

$$x_0 = x_4, x_1 = x_3, x_2 = 1 - 2(x_0 + x_1). \quad (13)$$

Equation (10) is accordingly simplified as

$$\frac{dX_0}{dt} = \left(-X_0 + \frac{3v_+(\text{I}_a)}{4(3v_+(\text{I}_a) + 2v_-(\text{II}))} X_1 + \frac{v_-(\text{II})}{8(3v_+(\text{I}_a) + 2v_-(\text{II}))} \right) \frac{v_-(\text{I}_a)v_-(\text{II})}{(3v_+(\text{I}_a) + v_-(\text{II}))P_E}, \quad (14)$$

$$\frac{dX_1}{dt} = \left(\frac{1}{2} - 2X_1 \right) \frac{v_-(\text{I}_a)v_-(\text{II})}{(3v_+(\text{I}_a) + 2v_-(\text{II}))P_E}, \quad (15)$$

$$\frac{dX_2}{dt} = -2 \left(\frac{dX_0}{dt} + \frac{dX_1}{dt} \right). \quad (16)$$

By using the initial condition of reaction, $X_0 = 0.5$ and $X_1 = 0$, the following equation is derived from Eqs. (14) and (15):

$$\left(\frac{dX_0}{dX_1} \right)_0 = \left(-1 + \frac{v_-(\text{II})}{4(3v_+(\text{I}_a) + 2v_-(\text{II}))} \right) \frac{3v_+(\text{I}_a) + 2v_-(\text{II})}{3v_+(\text{I}_a) + v_-(\text{II})}. \quad (17)$$

Second term in the parentheses of Eq. (17) attains a maximum value of 1/8 when $v_+(\text{I}_a)/v_-(\text{II}) = 0$, and hence it is neglected as compared with unity. Accordingly, we have

$$v_+(\text{I}_a)/v_-(\text{II}) = \left\{ 2(dX_0/dX_1)_0 - 1 \right\} / 3 \quad (18)$$

from Eqs. (16) and (17). Initial evolution rate of d_1 -ethylene, on the other hand, is given by Eq. (8) as

$$V_0^{E_1} = P_E(dX_1/dt)_0. \quad (19)$$

Substituting dX_1/dt of Eq. (15) into Eq. (19) we have

$$v_-(\text{I}_a) = 2V_0^{E_1}(3v_+(\text{I}_a)/v_-(\text{II}) + 2). \quad (20)$$

Thus, the unidirectional rates of steps I_a and II can be evaluated according to Eqs. (5), (18) and (20) by measurements of V_s , V^{E_1} and V^{E_2} .

Backward rate of step I_b is given by Eqs. (3) and (11) by taking account of the initial condition of reaction, $Y_1 = 0$, as

$$v_-(\text{I}_b) = 2V_0^{\text{PPD}}, \quad (21)$$

and, accordingly, forward rate of step I_b is evaluated by Eq. (5).

Ratio of $v_-(\text{II})$ to $v_+(\text{I}_a)$ is evaluated otherwise from the evolution rates of deuterio-ethanes as follows. In the present reaction, the evolution rate of d_n -ethane is given in terms of x_0 , x_1 and $V_s (= v_+(\text{III}))$ as

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$$\left. \begin{aligned} V^{A_0} &= V^{A_s} = x_0 V_s / 4, \\ V^{A_1} &= V^{A_s} = (x_0/2 + x_1/4) V_s, \\ V^{A_2} &= V^{A_s} = (1 - x_0) V_s / 4 = (1/4 - V^{A_0}) V_s, \\ V^{A_3} &= (1/2 - x_0 - x_1/2) V_s = (1/2 - 2V^{A_1}) V_s, \end{aligned} \right\} \quad (22)$$

according to Eqs. (4), (11) and (13). In Eqs. (22) x_0 and x_1 at initial stage of the reaction are expressed as solutions of Eq. (6) as

$$x_0 = \frac{3}{6 + 2R} + \frac{R^2}{8(3 + R)(3 + 2R)}, \quad (23)$$

$$x_1 = \frac{R}{2(3 + 2R)}, \quad (24)$$

where $R \equiv v_{-}(\text{II})/v_{+}(\text{I}_a)$. According to these equations, the relative evolution rates V^{A_n}/V_s 's at the initial stage are calculated as functions of R as shown in Figs. 1 a) and b). With reference to these figures, the values of R can be estimated by measuring V^{A_n}/V_s 's.

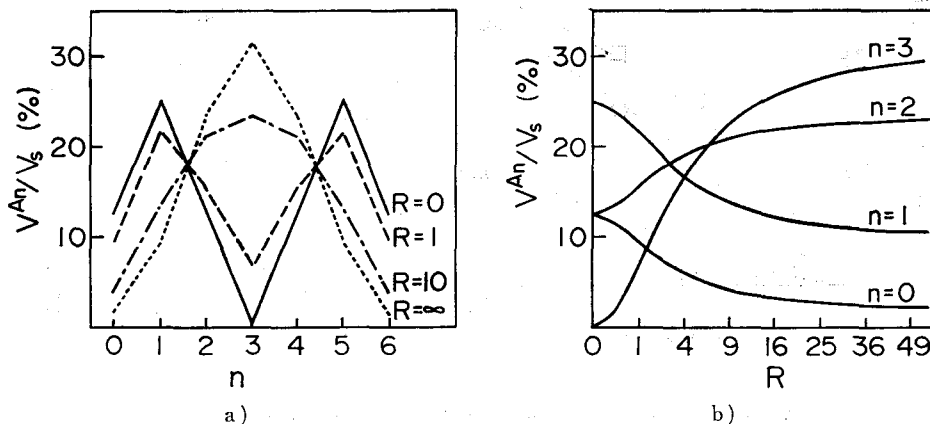


Fig. 1. Calculated evolution rates of deuterio-ethanes at the initial stage of reaction of an equimolar mixture of C_2P_4 and C_2D_4 with an equimolar mixture of P_2 and D_2 . ($R \equiv v_{-}(\text{II})/v_{+}(\text{I}_a)$).

Experimental

Apparatus, materials and experimental procedures are the same as described in the previous papers.¹⁻³⁾ Reaction was carried out with equimolar C_2P_4 , C_2D_4 , P_2 and D_2 at 40 mmHg of the initial total pressure and reacting gas was sampled at times for mass-spectrometric analysis.¹⁾

Results and Discussion

Reaction on Cu film. Reaction was carried out at 101 and 137°C and time courses of d_1 -ethylene evolution are plotted in Figs. 2 a) and b). Relatively large amount of d_3 -ethylene is due to reactant ethylene originally involving *ca.* 2% of d_3 -ethylene. Relative rates of steps I_a and II are evaluated as given in Table 1 from the evolution rates of d_1 - and d_2 -ethylene after the induction period. Table 1 shows that both of steps I_a and II are far faster than hydrogenation of ethylene and step I_a is *ca.* 2.4 times as fast as step II.

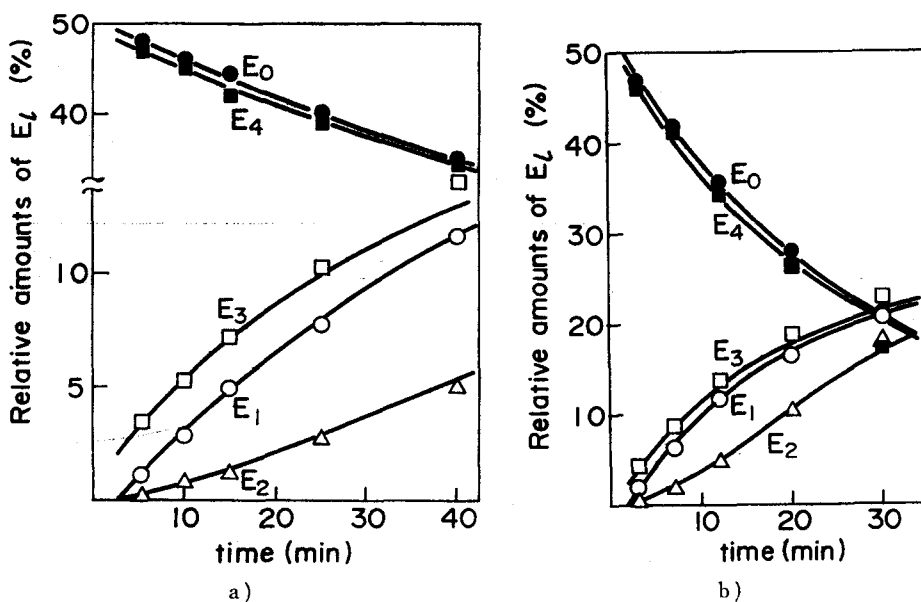


Fig. 2. Hydrogen mixing between C_2P_4 and C_2D_4 during the reaction on Cu film with equimolar C_2P_4 , C_2D_4 , P_2 and D_2 at 101°C (a) and 137°C (b).

TABLE 1. Evolution rates of d_1 - and d_2 -ethylene and relative rates of steps I_a and II at the initial stage of reaction with equimolar C_2P_4 , C_2D_4 , P_2 and D_2 on Cu film.

$P_E = P_H = 20$ mmHg.

Temp. (°C)	$\frac{dX_1}{dt}$ (%/min.)	$\frac{dX_2}{dt}$ (%/min.)	$v_+(I_a)/V_s$	$v_+(II)/V_s$
101	0.43	0.10	610	250
137	1.6	0.39	740	310

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In order to make sure the result of Table 1, the time course of hydrogen mixing in ethylene was simulated according to Eqs. (5) and (10) by a computer. In this simulation, the origin of reaction time is adjusted to the end of induction period, y_1 is set constantly at 0.5, the initial values of X_i 's and P_E are adjusted to the experimental condition, and the values of $v_-(I_a)$ etc. are given from Table 1 as constants throughout the time course. Results of the simulation according to Runge-Kutta-Gill method¹¹⁾ are shown in Figs. 2 a) and b) with full lines. Good agreement between the simulation and the experiment suggests adequacy of the presumptions for simulation, *i. e.*, (i) hydrogen mixing in ethylene takes place *via* steps I_a and II of scheme (1), (ii) the rates of these steps are given according to Eqs. (5), (18) and (20), and (iii) isotopic effect on the rate of hydrogen mixing in ethylene is negligible.

The rates of these steps evaluated previously¹⁾ from the results of ethylene deuteration are considerably smaller than the present ones owing to the inaccurate measurement of the evolution rates of deuterio-ethanes in the previous work.¹⁾

Rate of step I_b in this reaction was not determined since simultaneous P_2 - D_2 equilibration was immeasurably slow.

Reaction on Rh film. Table 2 shows the results of reaction carried out at temperatures from -45 to 23°C with evaporated Rh film. Relative rates of steps I_a and II given in Table 2 are in agreement with those evaluated previously³⁾, indicating that the previous method mainly based on analysis of the evolution rates of deuterio-ethanes is sufficiently reliable in a case of steps I_a and II being relatively slow. Figure 3 shows the distribution of deuterio-ethanes formed by the reaction at -13°C ; the fraction Z_n of d_n -ethane is equal to V^{A_n}/V_s in this case since the distribution of deuterio-ethanes is practically unchanged throughout the reaction. Even though the mass-spectrometric analysis of deuterio-ethanes is not accurate, the distribution shown in Fig. 3 is obviously far from its equilibrium. With

TABLE 2. Evolution rates of d_1 - and d_2 -ethylene and relative rates of steps I_a and II at the initial stage of reaction on Rh film. $P_E = P_H = 20$ mmHg.

Temp. ($^\circ\text{C}$)	dX_1/dt (%/min.)	dX_2/dt (%/min.)	$v_+(I_a)/V_s$	$v_+(II)/V_s$
23	2.3	1.0	2.3	2.9
0	0.92	0.48	1.9	3.0
-22	0.15	0.07	1.5	2.4
-45	0.08	0.07	1.6	2.2

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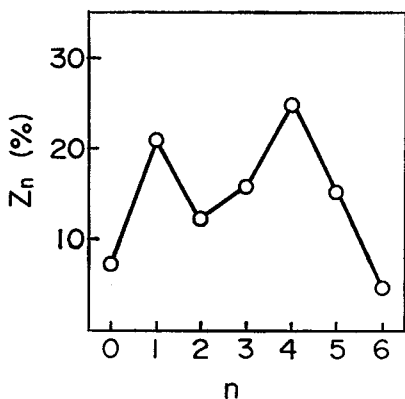


Fig. 3. Distribution of deuterio-ethanes formed by the reaction on Rh film with equimolar C_2P_4 , C_2D_4 , P_2 and D_2 at $-13^\circ C$.

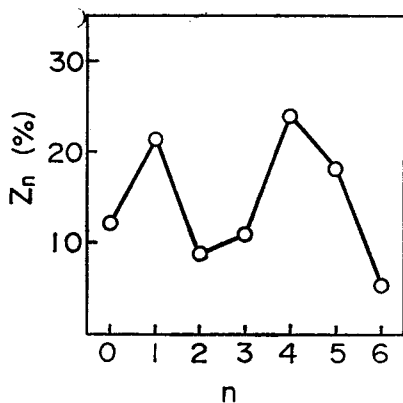


Fig. 4. Distribution of deuterio-ethanes formed by the reaction on Pt film at $53^\circ C$.

distribution of deuterio-ethanes produced by the reaction (Fig. 4), the value of R is estimated to be nearly equal to that on Rh film in agreement with the previous result.³⁾

TABLE 3. Relative rates of steps I_a and II on Ni film estimated by the simulation method.

Temp. ($^\circ C$)	$v_+(I_a)/V_s$	$v_+(II)/V_s$
45	29	25
24	24	32
0	30	36

reference to Fig. 1, the value of R ($\equiv v_-(II)/v_+(I_a)$) is estimated as 3~5 in agreement with the above conclusion.

The present method is not applicable to evaluation of the rate of step I_b , since the step is composed of two elementary steps as concluded previously,³⁾ while the previous method^{2,3)} is still useful.

Reaction on Ni film. Relative rates of steps I_a and II were estimated as given in Table 3 by simulating the time course of deuterio-ethylene formation observed in the previous work²⁾; these rates obtained are larger than those evaluated previously²⁾ similarly to the case of Cu film.

Reaction on Pt film. Hydrogen mixing in ethylene was so slow that the evolution rate of d_2 -ethylene was not determined accurately. From the

Summary

It was shown that the rates of steps I_a and II of scheme (1) can be evaluated easily and accurately from the rate of hydrogen mixing between C_2P_4 and C_2D_4 during the reaction of an equimolar mixture of C_2P_4 and

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C_2D_4 with an equimolar mixture of P_2 and D_2 . The present method is especially useful in a case of ethylene hydrogenation accompanying fast hydrogen mixing in ethylene. Differences between the present and the previous results are mainly due to error in the mass-spectrometric analysis of deuterioethanes in the previous works,¹⁻³⁾ but the error is not so significant as to revise the previous conclusions on the reaction structure of ethylene hydrogenation.

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