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HYDROGEN ELECTRODE REACTION ON
NICKEL IN ALKALINE SOLUTIONS

Part 2. Current-Overvoltage Relation of the Discharge Step

By

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Abstract

The kinetic law of the discharge step of the hydrogen evolution reaction on nickel in aqueous sodium hydroxide was determined from the overvoltage-time curves after switching-on of the polarizing current. It was found that the relation between the rate and overvoltage of the discharge step is expressed by the equation developed by FRUMKIN and ALADJALOVA with respect to the discharge step of the hydrogen evolution reaction on palladium.

Introduction

The rate of the hydrogen evolution reaction on nickel in alkaline solutions is limited by the elementary step of the recombination of adsorbed hydrogen atoms. However the affinity of the discharge step is not completely negligible even in the steady state of the overall reaction and may possibly be developed to its full extent in the transient state. The latter situation enables us to establish the kinetic law of the discharge step of the reaction by the galvanostatic transient method. In Part 1, the exchange rate of the discharge step of the reaction was found by this method to be proportional to the square root of sodium ion concentration independent of pH, indicating that the discharge step of the reaction consists in the discharge of sodium ion as in the case of platinum. The present work is purposed to establish the current-overvoltage relation of the discharge step of the hydrogen evolution reaction on nickel in aqueous sodium hydroxide by means of galvanostatic transient method.

The rate of the discharge step can be determined from the displacement of overvoltage after switching on a polarizing current by the following equation, provided that the displacement of overvoltage is caused by charging up of the double layer at the metal-solution interface and the differential capacity of the double layer is known:

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where $i_1$—the rate of the discharge step expressed in the electric unit, $i$—the applied current density, $C_D$—the differential capacity of the electric double layer, $\eta$—the overvoltage, $\dot{\eta}$—the rate of the displacement of overvoltage. The sign of the current is taken positive and that of $\eta$ negative in the cathodic direction.

The value of $C_D$ at the definite value of $\eta$ is given by the following expression using the initial tangent of the $\eta-t$ curve which starts from that value of $\eta$:

$$C_D = -\left( \frac{\Delta i}{\dot{\eta}} \right)_{t=0}$$

where $\Delta i$ denotes the increment of the polarizing current density.

The displacement of overvoltage after switching on a constant polarizing current is however in general affected not only by charging up of the double layer, but also by accumulation of the intermediate species of the reaction or specifically adsorbed ions. Thus it is necessary to observe very fast change of overvoltage which is caused solely by charging up of the double layer in order
to deduce the rate of the discharge step from the overvoltage-time curve on
the basis of Eq. (1).

Experimental Results and Discussion

In the present work the overvoltage-time curves were observed on evaporated nickel film electrodes within a few milliseconds after switching on a
constant polarizing current, following the same procedures as described in the
previous work.\cite{8,11} Fig. 1 shows the overvoltage dependence of $C_D$ calculated
by Eq. (2) from the $\eta - t$ curves observed with a nickel film electrode of
apparent area 0.03 cm$^2$ in NaOH$_{aq}$ of pH 12.2.

As seen from this Figure, the value of $C_D$ practically remains constant
at 3.4 $\mu$F independent of $\eta$. It may be assumed from the constancy of $C_D$
that there is no necessity for taking into consideration the effect of the specific
adsorption of ions or intermediate species on the displacement of overvoltage
in such very fast change of overvoltage as observed.

Fig. 2 shows the relation between $i_1$ and $\eta$ calculated by Eq. (1) from the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{The relation between $i_1$ and $\eta$ obtained from the build up curve
observed in NaOH$_{aq}$ of pH 12.8 at current densities: (□): $i=2$
35-$10^{-4}$ A/cm$^2$ (●): $i=5.58-10^{-4}$ A/cm$^2$ (○): $i=1.03-10^{-3}$ A/cm$^2$.}
\end{figure}
$\eta-t$ curves observed with lower current densities in $\text{NaOH}_aq$ of pH 12.8. The values of $i_1$ and $i$ in Fig. 2 are expressed by the current density per true unit area, using the $C_D$-value 18 $\mu$F/cm$^2$ which is the differential capacity of the double layer of the mercury electrode reported by VORSINA and FRUMKIN.\textsuperscript{14)} As seen from Fig. 2, $i_1$ increases proportionally to $\eta$ in the neighborhood of $\eta=0$ with a constant gradient independent of the applied current density and

**Fig. 3.** The relation between $i_1$ and $\eta$ obtained from the build up curve observed in $\text{NaOH}_aq$ of pH 13.0 at current densities: (+): $i=1.41\cdot10^{-3}$ A/cm$^2$ (Δ): $i=5.34\cdot10^{-3}$ A/cm$^2$ (●): $i=2.40\cdot10^{-2}$ A/cm$^2$ (⊙): $i=4.94\cdot10^{-2}$ A/cm$^2$ (■): $i=1.00\cdot10^{-1}$ A/cm$^2$. 

T. OHMORI and A. MATSUDA
then deviates downward from the proportionality along with increase of $\eta$. The reaction resistance $r_{10}$ defined as $(\partial\eta/\partial i_t)_{t=0}$ is found 9.8 $\Omega \cdot \text{cm}^2$ from Fig. 2, which coincides with the value previously obtained from the time constant of the discharge step $\tau_1$ at $\eta=0$.\(^{10}\) The exchange current of the discharge step $i_{10}$ calculated from $r_{10}$ by Eq. (3) in Part 1 is $2.6 \times 10^{-3}$ A/cm\(^2\), which is far larger than the exchange rate of the overall reaction $i_0=7.4 \times 10^{-6}$ A/cm\(^2\) obtained from the extrapolation of the Tafel line.\(^{9}\) This fact verifies that the

Fig. 4. The relation between $\log i_t$ and $\gamma$ obtained from Fig. 3 \((\circ)\), and the log $i-\gamma$ relation in steady states \((\circ)\) in NaOH\(_{aq}\) of pH 13.0; \((-\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cd-

discharge step is not rate-determining in the hydrogen evolution reaction at the reversible hydrogen electrode potential.

Fig. 3 shows the relation between \( i_t \) and \( \eta \) calculated by Eq. (1) from the \( \eta-t \) curves observed with higher current densities in \( \text{NaOH}_{aq} \) of pH 13.0. As seen from this Figure, \( i_t \) first increases proportionally to \( \eta \) in the neighborhood of \( \eta=0 \) as in the case of Fig. 2 and then increases exponentially with increase of \( \eta \) contrary to the case of Fig. 2 and latter deviates from the exponential relation. The deviation of the \( i_t-\eta \) curve from the exponential relation begins at higher overvoltage when the polarizing current is increased. Now the logarithm of \( i_t \) in Fig. 3 is plotted against \( \eta \) in Fig. 4. For comparison,
Hydrogen Electrode Reaction on Nickel in Alkaline Solutions

the log $i_1 - \eta$ curve in steady states is also shown in this Figure. As seen from this Figure, the relation between log $i_1$ and $\eta$ can be separated in two stages. The first stage can be expressed by Tafel's formula with the coefficient 1/2, i.e.,

$$i_1 = i_{10} \left\{ \exp \left( \frac{F \eta}{2 RT} \right) - \exp \left( -\frac{F \eta}{2 RT} \right) \right\}, \tag{3}$$

where $F$, $R$, and $T$ denote Faraday, the gas constant and the absolute temperature respectively. As reported in Part 1, $i_{10}$ is proportional to the square root of the sodium ion concentration,

$$i_{10} = k (C_{Na^+})^{1/2}. \tag{4}$$

The concentration dependence of the first stage of the log $i_1 - \eta$ curve is shown in Fig. 5. It can be seen from this Figure that the overvoltage at a constant value of $i_1$ is shifted to the negative side by ca. 65 mV with decrease of the concentration of solution by one order. It is found from these results that the relation between $i_1$ and $\eta$ deduced from the initial stage of the $\eta - t$ curve on the basis of Eq. (1) can be expressed by the equation developed by Frumkin and Aladjalova with respect to the discharge step of the palladium hydrogen electrode reaction. In the second stage where the log $i_1 - \eta$ relation deviates from Tafel's formula, the change of overvoltage may be caused by the accumulation of the intermediate species produced by the discharge step rather than by charging up of the double layer. The distribution of overvoltage among constituent elementary steps will be discussed in later works.

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