199. Effect of Mass Diffusion on Nitration Rates of Moderately Reactive Aromatic Substrates

by **Kenji Fujiwara, Masamitsu Tamura** and **Tadao Yoshida**

Department of Reaction Chemistry, Faculty of Engineering, The University of Tokyo, Hongo,
Bunkyo-ku, Tokyo 113, Japan

(6.III.80)

Summary

Competitive nitrations of two pairs of aromatic substrates were carried out in order to clarify the effect of several methods of mixing on the observed relative rates.The experimental results indicate that a commercially available four-jet mixer for rapid reaction could not achieve homogeneous mixing in the competitive nitration of aromatic substrates in aqueous sulfuric acid.

1. Introduction. - The competitive nitration is a convenient method for determining the relative rates of nitrations of aromatic substrates. It has been extensively employed for the studies of nitration mechanism [1-3]. However, competitive rate determination has such limitations as that the obtained relative rates are sometimes disguized by mass diffusion as have been discussed by several workers [4-6].

In the beginning of this study, we intended to clarify the valid range and limitations of a commercially available four-jet mixing device which was used as a part of a stopped flow apparatus. After starting the experiment, it became clear that the mixing efficiency by the mixing device was not better than that by an ordinary Y-tube when applied to competitive nitration in aqueous sulfuric acid. This investigation aimed at examining the mixing efficiency of several methods, especially the four-jet mixer. The following methods for mixing were used: Y-tube method, dropwise addition under stirring, four-jet mixing method and four-jet mixing method with subsequent stirring. After some preliminary experiments, two pairs of moderately reactive aromatic substrates, *o-/m*-nitrotoluenes and 2-nitro-*m*-xylene/*p*-nitrotoluene, were chosen as substrates.

2. Results and Discussion. - *Figure 1* shows the relationship between the observed first-order rate constant and the concentration of nitric acid for the nitration of dilute *o*- and *m*-nitrotoluenes in 97% sulfuric acid. The intrinsic relative rate of *o*- over *p*-nitrotoluene was 3.15. *Olah et al.* [7] obtained 3.81 for the relative rate using non-competitive nitration with nitronium tetrafluoroborate in 96% sulfuric acid.

0018-019X/80/7/1897-08$01.00/0

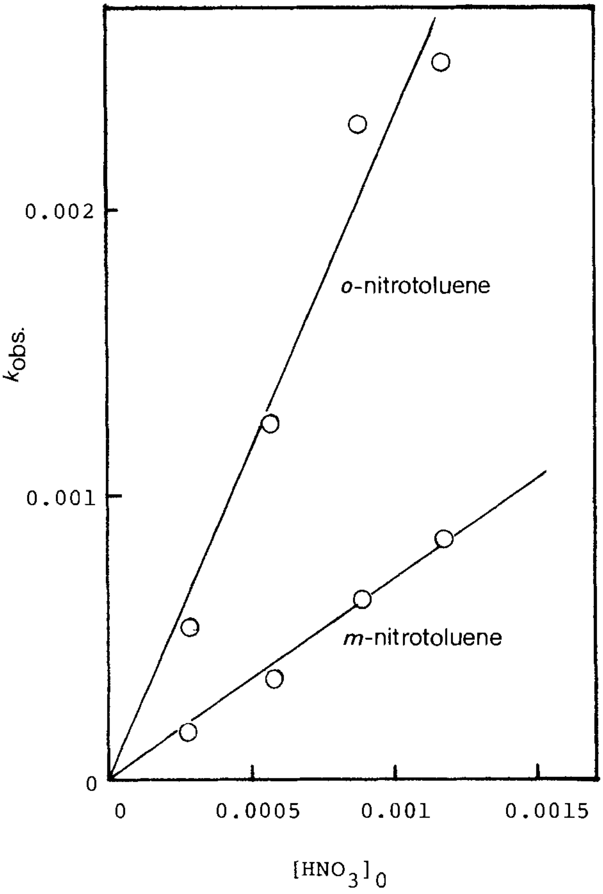

Fig. 1. *Variation of the observed first-order rate constants with initial concentration of nitric acid for the nitration in 96.5% sulfuric acid at 25°*

The relative rates in the competitive nitration of the substrates in the same medium over the initial concentration of the reactants are listed in *Table 1* and shown in *Figure 2*. The relative rates obtained by adding a nitrating solution to a solution of the substrates under vigorous stirring were constant at *ca.* 3.3 within the range of the employed concentration of the reactants.

On the other hand, in the case of the Y-tube or the four-jet mixing methods, the relative rates decreased with the increasing concentration of the reactants, as shown in *Figure 2*. Results shown in *Figure 2* suggest that the mixing by these two methods were less efficient than by the dropwise addition under stirring.

The relative rates of 2-nitro-*m*-xylene to *p*-nitrotoluene in the competitive nitration in 91% sulfuric acid are listed in *Table 2* and shown in *Figure 3*. 2-Nitro-*m*-xylene is most reactive of the four substrates used and its nitration rate in 91% sulfuric acid is expected to be faster than that in 97% sulfuric acid as generally observed [8]. In this case, all relative rates by above three mixing methods decreased with the increasing concentration of the reactants, while they were in the increasing order of dropwise addition under stirring, >Y-tube method, >four-jet mixing

Table 1. *Relative rates of* o-*nitrotoluene to* m-*nitrotoluene for the competitive nitration with nitric acid in 96.5% sulfuric acid at 25° for different concentrations of the components and for different mixing methods*

Run	*o*-Nitrotoluene (M)	*m*-Nitrotoluene (M)	*p*-Nitrochlorobenzene[a]) (M)	Nitric acid (M)	Relative rate
Y-Tube method					
H-63	9.20×10^{-4}	9.75×10^{-4}	9.30×10^{-4}	1.00×10^{-3}	3.24
H-62	1.84×10^{-3}	2.00×10^{-3}	1.86×10^{-3}	2.00×10^{-3}	3.18
H-65	1.30×10^{-2}	1.34×10^{-2}	1.46×10^{-2}	1.38×10^{-2}	3.10
H-69	1.58×10^{-2}	1.60×10^{-2}	1.60×10^{-2}	1.60×10^{-2}	3.04
H-66	2.36×10^{-2}	2.33×10^{-2}	2.13×10^{-2}	2.64×10^{-2}	3.19
H-64	5.05×10^{-2}	4.94×10^{-2}	4.48×10^{-2}	5.35×10^{-2}	2.64
H-67	1.02×10^{-1}	1.00×10^{-1}	9.35×10^{-1}	1.03×10^{-1}	2.16
H-68	1.98×10^{-1}	2.00×10^{-1}	2.00×10^{-1}	2.00×10^{-1}	2.01
Dropwise addition under stirring					
RMX-63	9.20×10^{-4}	9.80×10^{-4}	9.30×10^{-4}	1.00×10^{-2}	3.31
RMX-62	1.84×10^{-3}	2.00×10^{-3}	1.86×10^{-3}	2.00×10^{-3}	3.37
RMX-58	3.66×10^{-3}	3.68×10^{-3}	3.53×10^{-3}	3.91×10^{-3}	3.45
RMX-65	1.30×10^{-2}	1.34×10^{-2}	1.45×10^{-2}	1.38×10^{-2}	3.21
RMX-66	2.34×10^{-2}	2.33×10^{-2}	2.13×10^{-2}	2.64×10^{-2}	3.23
RMX-64	5.01×10^{-2}	4.94×10^{-2}	4.48×10^{-2}	5.35×10^{-2}	3.41
RMX-67	1.02×10^{-1}	1.00×10^{-1}	9.35×10^{-1}	1.03×10^{-1}	3.37
Four-jet mixing method					
R-40	2.28×10^{-3}	2.54×10^{-3}	1.89×10^{-3}	2.28×10^{-3}	3.14
R-99	3.74×10^{-3}	3.78×10^{-3}	3.38×10^{-3}	3.22×10^{-3}	3.11
R-49	6.00×10^{-3}	5.60×10^{-3}	4.84×10^{-3}	5.10×10^{-3}	3.10
R-100	1.50×10^{-2}	1.50×10^{-2}	1.35×10^{-2}	1.60×10^{-2}	3.08
R-98	4.84×10^{-2}	4.70×10^{-2}	6.05×10^{-2}	4.91×10^{-2}	2.66
R-69	9.55×10^{-2}	9.80×10^{-2}	1.03×10^{-2}	9.70×10^{-2}	2.26
R-105	1.03×10^{-1}	1.02×10^{-1}	1.02×10^{-1}	1.00×10^{-1}	1.97
Four-jet mixing method with subsequent stirring					
MXR105	1.03×10^{-1}	1.02×10^{-1}	1.02×10^{-1}	1.00×10^{-1}	3.24

[a]) As an internal standard.

method. As discussed by *Rys et al.* [5], the deviation of a relative rate from the intrinsic one could be ascribed to the effect of mass diffusion on the chemical reaction rate. The deviation is larger where the influence of mass diffusion is greater. *Figure 3* suggests that the four-jet mixing method was most affected by the mass diffusion among three mixing methods. This was unexpected since this device has been often used for rapid homogeneous mixing in the studies of fast reactions.

In order to find out whether the trend shown in *Figure 3* is a common or special case, additional competitive nitrations were carried out, using nitronium hexafluorophosphate as a nitration agent and dried pure nitromethane as a solvent. The viscosity of nitromethane is lower than that of the sulfuric acid used above. The results are listed in *Table 3* and *4*. The relative rates were greater for both pairs of the substrates in the four-jet mixing method than in the Y-tube method. This indicates that the former exhibits better efficiency of mixing than the latter, in nitromethane solvent.

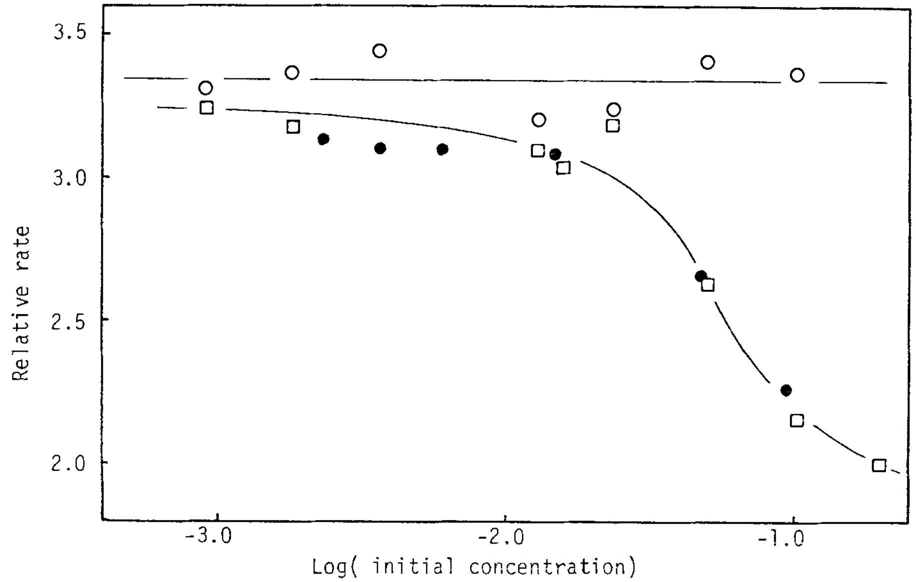

Fig. 2. *Relative rate of* o- *to* m-*nitrotoluene against the logarithm of initial concentration of* o-*nitrotoluene in the nitration with nitric acid in 96.5% sulfuric acid at 25°*
○ Dropwise addition under stirring. □ Y-Tube method. ● Four-jet mixing method

Another experiment was performed to clarify what part of the device the reaction took place which affected the observed relative rate most. The concentration chosen for *o*- and *m*-nitrotoluenes, nitric acid and nitronium salt was 0.1 mol/l, and 97% sulfuric acid and dried nitromethane were used as the reaction media. When the reaction was stopped immediately after mixing by the four-jet mixer (see *Fig. 4*), the conversions of nitrating agents were less than 15% both in 97% sulfuric acid and in nitromethane. This means that most of the reactions proceeded after the completion of the four-jet mixing. The relative rates in the nitration in 97% sulfuric acid by the four-jet mixing method and by the four-jet mixing method with subsequent stirring were 2.0 and 3.2, respectively as listed in *Table 1* (Run R-105 and MXR 105), while the relative rates of the nitration in nitromethane by both mixing methods were similar as listed in *Table 3* (Run R-106 and MXR 106). In the nitration in 97% sulfuric acid, the relative rate (3.2) was intrinsic. This means that the reaction proceeded in a homogeneous solution in the case of the four-jet mixing method with subsequent stirring.

The results in 97% sulfuric acid suggest that the four-jet mixer was not efficient enough to mix the reactant solutions homogeneously in the nitration in 97% sulfuric acid and that the efficiency of mixing was less than those by the dropwise addition under stirring and even by the Y-tube method. The results in nitromethane suggest that the efficiency of mixing by the four-jet mixing method was similar to that by the dropwise addition under stirring and better than by the Y-tube method.

At the moment, it is difficult to give a clear explanation to the relative rate (2.4) observed by the four-jet mixing method with and without subsequent stirring.

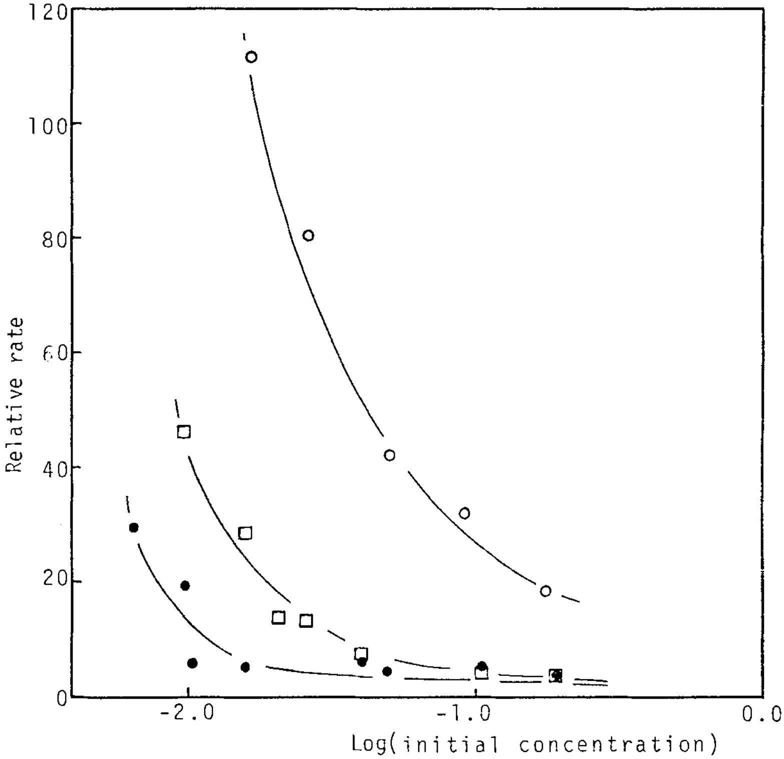

Fig. 3. *Relative rate of 2-nitro-*m*-xylene to* p*-nitrotoluene against the logarithm of initial concentration of 2-nitro-*m*-xylene in the nitration with nitric acid in 90.7% sulfuric acid at 25°*
○ Dropwise addition under stirring. □ Y-Tube method. ● Four-jet mixing method

Olah et al. [3] reported the relative rate of 3.5 for a non-competitive nitration using a flow-quenching apparatus. This difference of relative rates obtained may be due to the efficiency difference of the two mixing devices employed by *Olah et al.* and by us, since the scale of the systems are so different.

Another situation makes the problem complicated. As discussed in our paper [9], the observed nitration rates of aromatic nitro compounds are affected by hydrogen bonding in a concentrated sulfuric acid solvent. So the relative rates which are not disguised by mass diffusion may be different in the two solvents: sulfuric acid and nitromethane.

3. Conclusion. - The four-jet mixer and similar rapid mixing devices are widely used as a part in stopped flow apparatus, continuous flow, and flow-quenching apparatus which are designed for the studies of the kinetics of rapid chemical reactions. However, the mixing cannot make the solution homogeneous enough, so the intrinsic nitration rates of moderately reactive substrates can not be observed in sulfuric acid as solvent.

4. Experimental. - *Materials. p*-Nitrotoluene, 2,4-dinitrotoluene, 2,4-dinitro-*m*-xylene and *p*-nitrochlorobenzene were purified by recrystallization. Commercial 2-nitro-*m*-xylene, *p*-dinitrobenzene, *o*- and *m*-nitrotoluenes were used without further purification. Spectroscopic grade nitromethane and

Table 2. *Relative rates of 2-nitro-*m*-xylene to* p*-nitrotoluene for the competitive nitration with nitric acid in 90.6% sulfuric acid at 25° for different concentrations of the components and for different mixing methods*

Run	2-Nitro-*m*-xylene (M)	*p*-Nitrotoluene (M)	Dinitrobenzene[a]) (M)	Nitric acid (M)	Relative rate
Y-Tube method					
H-29	9.75×10^{-3}	9.50×10^{-3}	5.15×10^{-3}	1.04×10^{-2}	46.1
H-25	1.59×10^{-2}	1.60×10^{-2}	7.45×10^{-3}	1.28×10^{-2}	28.7
H-22	2.04×10^{-2}	2.03×10^{-2}	1.86×10^{-2}	2.03×10^{-2}	13.7
H-17	2.58×10^{-2}	2.61×10^{-2}	1.00×10^{-2}	2.60×10^{-2}	13.5
H-19	4.11×10^{-2}	4.07×10^{-2}	2.67×10^{-2}	4.37×10^{-2}	7.6
H-23	1.05×10^{-1}	1.03×10^{-1}	3.54×10^{-1}	1.15×10^{-1}	4.1
H-24	1.91×10^{-1}	1.93×10^{-1}	6.90×10^{-1}	1.79×10^{-1}	4.0
Dropwise addition under stirring					
RMX-102	1.66×10^{-2}	1.63×10^{-2}	1.05×10^{-2}	1.66×10^{-2}	112.2
RMX-98	2.64×10^{-2}	2.63×10^{-2}	1.37×10^{-2}	2.64×10^{-2}	80.6
RMX-104	4.99×10^{-2}	4.95×10^{-2}	2.25×10^{-2}	5.02×10^{-2}	42.5
RMX-93	9.03×10^{-2}	8.98×10^{-2}	4.52×10^{-2}	9.06×10^{-2}	32.1
RMX-92	1.72×10^{-1}	1.72×10^{-1}	7.40×10^{-1}	1.72×10^{-1}	18.4
Four-jet mixing method					
R-16	6.50×10^{-3}	6.50×10^{-3}	2.50×10^{-3}	6.46×10^{-3}	29.8
R-29	9.75×10^{-3}	9.50×10^{-3}	5.15×10^{-3}	1.04×10^{-3}	19.6
R-18	1.03×10^{-2}	1.04×10^{-2}	4.00×10^{-2}	1.04×10^{-2}	6.0
R-25	1.59×10^{-2}	1.60×10^{-2}	1.28×10^{-2}	1.28×10^{-2}	5.1
R-19	4.11×10^{-2}	4.07×10^{-2}	2.67×10^{-2}	4.37×10^{-2}	6.2
R-28	4.88×10^{-2}	4.00×10^{-2}	2.58×10^{-2}	1.63×10^{-2}	4.6
R-23	1.05×10^{-1}	1.03×10^{-1}	3.54×10^{-1}	1.15×10^{-1}	5.5
R-24	1.91×10^{-1}	1.93×10^{-1}	6.90×10^{-1}	1.79×10^{-1}	4.0

[a]) As an internal standard.

Table 3. *Relative rates of* o*-nitrotoluene to* m*-nitrotoluene for the competitive nitration with nitronium hexafluorophosphate in nitromethane at room temperature for different concentrations of the components and for different mixing methods*

Run	*o*-Nitrotoluene (M)	*m*-Nitrotoluene (M)	*p*-Nitrochlorobenzene[a]) (M)	Nitronium salt (M)	Relative rate
Y-Tube method					
HN-56	1.85×10^{-1}	1.75×10^{-1}	1.79×10^{-1}	2.29×10^{-1}	2.00
Dropwise addition under stirring					
R-106	1.10×10^{-1}	1.12×10^{-1}	1.11×10^{-1}	1.14×10^{-1}	2.37
R-56	1.86×10^{-1}	1.75×10^{-1}	1.79×10^{-1}	2.29×10^{-1}	2.40
Four-jet mixing method with subsequent stirring					
MXR-106	1.10×10^{-1}	1.12×10^{-1}	1.11×10^{-1}	1.14×10^{-1}	2.36

[a]) As an internal standard.

methylene chloride were dried using molecular sieve. Nitronium hexafluorophosphate was purchased from *Ozark-Mahoning Company* and purified by the method described previously [10]. Pure nitric acid was prepared by distillation under reduced pressure of 98% nitric acid with an equal volume of 98% sulfuric acid, and stored at − 10°. The compositions of aqueous sulfuric acid solutions were determined by titration with 0.1N NaOH.

Table 4. *Relative rates of 2-nitro-*m*-xylene to* p*-nitrotoluene for the competitive nitration with nitronium hexafluorophosphate in nitromethane at 25° for different concentrations of the components and for different mixing methods*

Run	2-Nitro-*m*-xylene (M)	*p*-Nitrotoluene (M)	Dinitrobenzene[a]) (M)	Nitronium salt (M)	Relative rate
Y-Tube method					
HN-11	7.84×10^{-2}	7.84×10^{-2}	4.22×10^{-2}	8.65×10^{-2}	25.4
HN-12	1.25×10^{-1}	1.25×10^{-1}	6.05×10^{-1}	1.29×10^{-1}	12.7
HN-14	1.51×10^{-1}	1.51×10^{-1}	6.95×10^{-1}	1.46×10^{-1}	12.6
HN-15	1.81×10^{-1}	1.81×10^{-1}	1.03×10^{-1}	1.86×10^{-1}	10.9
Four-jet mixing method					
RN-12	1.27×10^{-1}	1.25×10^{-1}	6.05×10^{-2}	1.29×10^{-1}	75.9
RN-14	1.55×10^{-1}	1.51×10^{-1}	6.95×10^{-2}	1.46×10^{-1}	80.3
RN-15	1.81×10^{-1}	1.81×10^{-1}	1.03×10^{-1}	1.86×10^{-1}	67.1

[a]) As an internal standard.

Preparation of the reactant solution. In 25 ml of 96.5% sulfuric acid, *o*- and *m*-nitrotoluenes were dissolved with *p*-nitrochlorobenzene as an internal standard. The solution of nitric acid was prepared similarly. The reactants were measured so they were of the same molecular amounts, ranging from 4.5×10^{-2} to 10 mmol.

In the case of the other competitive nitration in aqueous sulfuric acid of 2-nitro-*m*-xylene and *p*-nitrotoluene, they were dissolved with *p*-dinitrobenzene as an internal standard in 25 ml of 90.7% sulfuric acid. The reactants were measured so that they were of the same molecular amounts, ranging from 1.5×10^{-1} to 10 mmol.

In the case of nitration with nitronium hexafluorophosphate in nitromethane, dried nitromethane solutions of the nitronium salt and the substrates were used instead of sulfuric acid solutions of nitric acid and the substrates. The reactant solutions were prepared in a dry box with phosphorus pentoxide as a drying agent.

Mixing methods. - Y-Tube method. The reactant solutions (25 ml each) were placed in each leg of a Y-tube of 26 mm diameter. The Y-tube was dipped in a thermostat bath at 25° for 10 min and subsequently two solutions were mixed in the Y-tube by swinging. Then the reaction mixture was kept standing at 25° for about 1 h.

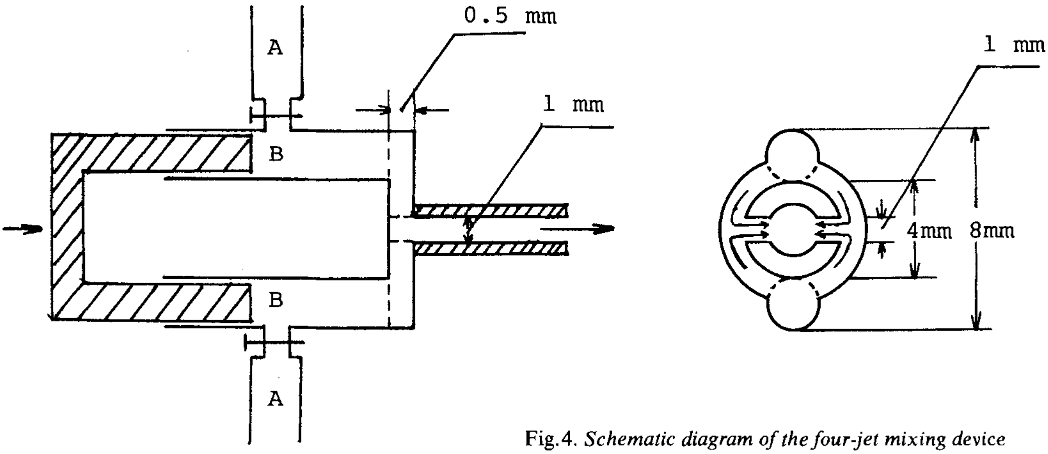

Fig. 4. *Schematic diagram of the four-jet mixing device*

Dropwise adding method under stirring. The solution of substrates was placed in a 100 ml three necked flask. The solution was vigorously agitated by a one-wing propeller (10 mm wide and 15 mm long). The speed of revolution was approx. 1000 rpm. The nitric acid solution was dropped into the solution of the substrates. The dropping rate was kept almost constant in all experiments. The stirring was continued for about 1 h at 25°.

Four-jet mixing method. Mixing device (*Union Giken Co.*, Osaka, Japan, Model MX-7) used was a part of the stopped flow apparatus of the same company used for the kinetics studies of fast reactions. The schematic diagram of the device is shown in *Figure 4.* Sample (0.625 ml) of each of the solutions were suctioned from the reservoirs (A) into each of two syringes (B) and then ejected through a tube of 1 mm diameter and 60 mm long into a small test tube of 10 mm diameter. The mixture was kept standing for about 1 h at 25°.

Four-jet mixing method with subsequent stirring. The four-jet mixing device was the same as above. The reaction mixture was ejected into a small flask equipped with a magnetic stirrer and immediately agitated for *ca.* 15 s. at room temperature.

Analysis. - After the reaction in sulfuric acid, the mixture was quenched in ice/water and extracted with methylene chloride. Washing the extract with $NaHCO_3$-solution (5%) and with water, drying with $MgSO_4$ and concentrating in an evaporator gave the sample containing the starting materials and dinitro compounds. The concentrations of the starting materials and some important products were determimed by gas liquid chromatography (GLC.) equipped with a thermal conductivity detector and 5 m×3 mm diameter stainless column of 80–100 mesh chromosorb WAW DMCS coated with 10% Apiezone grease L. The relative rates were calculated by the following equations:

$$k_{o\text{-NT}}/k_{m\text{-NT}} = \frac{\log([o\text{-NT}]/[o\text{-NT}]_0)}{\log([m\text{-NT}]/[m\text{-NT}]_0)} \qquad k_{\text{NX}}/k_{p\text{-NT}} = \frac{\log([\text{NX}]/[\text{NX}]_0)}{\log(1\text{-}[2,4\text{-DNT}]/[p\text{-NT}]_0)}$$

Here, *o*-NT, *m*-NT, *p*-NT, NX, and 2,4-DNT are abbreviations for *o*-, *m*-, and *p*-nitrotoluenes, 2-nitro-*m*-xylene, and 2,4-dinitrotoluene, respectively.

In the case of the nitration with the nitronium salt in nitromethane, the reaction mixture was quenched in 10 ml of diethyl ether about 10 min after the ejection. The sample for GLC. analysis was obtained by washing the ether extract with water, drying with $MgSO_4$ and concentrating in the evapolator. The relative rates were obtained by the same equations as above.

Non-competitive nitration. - Each of *o*- and *m*-nitrotoluene was dissolved in 96.5% sulfuric acid (10^{-4}-10^{-6} mol/l). Pure nitric acid was dissolved in 96.5% sulfuric acid at the concentration more than ten times as much as that of the substrates. The reactant solutions were mixed in a Y-tube at 25°. The mixture was transferred into a quartz cell of 10 mm photo path length, and the change of absorption intensity was observed by a UV. spectrophotometer (*Hitachi* Model 124) at a constant wave length.

The second-order rate constant k_2 was calculated by the following equation, where k_1 was the first-order rate constant obtained by the *Guggenheim* method.

$$k_2 = k_1/[\text{HNO}_3]_{\text{stoich}}$$

REFERENCES

[1] *C.K. Ingold*, 'Structure and Mechanism in Organic Chemistry', Cornell University Press, Ithaca (1953), Chap. 6.

[2] *M.J.S. Dewar, T. Mole & E.W.T. Warford*, J. chem. Soc., *1956*, 3576.

[3] *G.A. Olah*, ACS Symposium Series, *22*, 1 (1976).

[4] *W.S. Tolgyesi*, Can. J. Chem., *43*, 343 (1965).

[5] *F. Nabholz & P. Rys*, Helv. Chim. Acta, *60*, 2937 (1977) and references cited therein.

[6] *J.H. Ridd*, Accounts Chem. Res., *4*, 248 (1971).

[7] *G.A. Olah & H.C. Lin*, J. Amer. chem. Soc., *96*, 549 (1974).

[8] *J.G. Hoggett, R.B. Moodie, J.P. Penton & K. Schofield*, 'Nitration and Aromatic Reactivity', Cambridge University Press (1971) p. 17.

[9] *K. Fujiwara, Takayuki Andoh, Mitsuru Arai, Masamitsu Tamura & Tadao Yoshida*, J. org. Chem., in press.

[10] *T. Yoshida & J.H. Ridd*, ACS Symposium Series, *22*, 103 (1976).