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Atom-Efficient Benzoin Condensation in Liquid−Liquid System Using Quaternary Ammonium Salts: Pseudo-Phase Transfer Catalysis

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ABSTRACT: Benzoin condensation is a reaction of great commercial interest wherein two aromatic aldehydes are condensed to give benzoin (2-hydroxy-2-phenylacetophenone) product. Theoretically it is 100% atom economical. Several routes are used amongst which the metal cyanide catalysed reaction in homogeneous medium using alcohols as solvent is very popular. In the current work, benzoin condensation (dimerization) of two benzaldehyde molecules was carried out to give 2-hydroxy-2-phenylacetophenone (i.e., benzoin), in a biphasic catalytic system containing sodium cyanide and a phase transfer catalyst at 80 °C. Efficacy of various phase transfer agents such as tetra-*n*-butylammonium bromide (TBAB), tetramethylammonium bromide (TMAB), ethyltriphenylphosphonium bromide (ETPB), and tetrabutylammonium hydrogensulfate (TBAHS) was evaluated under otherwise similar reaction conditions. Use of two immiscible phases keeps contamination of cyanide ion in the organic phase negligible, and hence workup procedures are simpler. Under standard reaction conditions, with TBAB as catalyst, 75% conversion with >95% selectivity was obtained. Also, the aqueous phase was found to be reusable up to three times with good activity. An insight is provided as regards the actual mechanism. A kinetic model is developed on the basis of the experimental findings. Hitherto unknown facets of benzoin condensation are discussed with proper theoretical and experimental proof. This reaction is not the so-called phase transfer catalysis since there is no transfer of ion pairs once the reaction is initiated by the quaternary ion pair. The overall reaction is second order in benzaldehyde and first order in the quaternary ammonium salt of the cyanide ion. This is the first example of pseudo-phase transfer catalysis. The aqueous phase is reusable, unlike the traditional phase transfer catalysis procedures.

1. INTRODUCTION

In the course of organic synthesis, besides the desired products, many waste materials are also produced, which includes byproduct. These wastes should be destroyed and/or disposed of, which consumes much energy and puts a heavy burden on the environment. Hence waste minimisation of both materials and energy is of great importance. Perhaps one of the most general and efficient methodologies that fulfills this requirement is phase transfer catalysis. Phase transfer catalysis (PTC) is now a well investigated technique covering 600 odd processes, and the majority of these are conducted under liquid−liquid conditions leading to intensification of reaction rates and higher selectivity.[1−4] The reuse of catalyst is normally not attempted in L−L PTC, and the catalyst is removed from the organic phase by water washings and destroyed in the effluent treatment facilities along with the aqueous waste. There are no reports of phase transfer agents being used for dimerization reactions.

The α-hydroxycarbonyl group is an important synthon for the preparation of natural products, industrial materials, and pharmaceutical materials. Benzoin condensation is a reaction of great interest to organic chemists and biochemists wherein two aromatic aldehydes, particularly benzaldehyde, are condensed to give the benzoin product. In reality it is not a condensation but a dimerization reaction since no water is liberated. This is 100% atom economical since the molecules are added. Benzoin (2-hydroxy-2-phenylacetophenone or 2-hydroxy-1,2-diphenylethanone) is used for the synthesis of benzyl,[5,6] substituted indoles,[7] and oxazoles.[8] Out of various synthetic routes for introducing this moiety, the benzoin reaction and related additions are perhaps the most direct one. The original catalyst for benzoin condensation was KCN in aqueous alcohol, but various other catalysts have also been used such as thiazolium salts,[9−13] *N*,*N*′-disubstituted *o*-phenylenediamine,[14] bi(1,3-dialkylimidazolidin-2-ylidenes),[15] enzymes and their artificial analogues,[16,17] imidazolium salts,[18−22] etc. A thiazolium salt catalyzed mechanism and kinetics for this reaction have been studied in alcohols in homogeneous medium.[22] Aside from serving as a good model for the mode of action of the coenzyme thiamine pyrophosphate, thiazolium salts are of interest because they promote the formation of a carbon−carbon bond, with the attendant chiral center, under mild conditions.

We have investigated reaction kinetics and mechanism of various phase transfer catalysed reactions,[4a−h,23a−j] and it was thought worthwhile to study benzoin condensation in a biphasic system using quaternary ammonium salts, which are normally used as phase transfer catalysts. An insight is provided as regards the actual mechanism, the effect of various parameters was studied, and a kinetic model is developed on the basis of the experimental findings. The reaction is not a true PTC reaction but a pseudo-PTC since no actual transfer of ion pairs takes place across the interface and this is the first example of pseudo-phase transfer catalysis being reported here. Thus, the current work presents hitherto unknown facets of benzoin condensation with proper theoretical and experimental proof.

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2. EXPERIMENTAL SECTION

2.1. Materials. Toluene, *n*-dodecane, benzaldehye, and sodium cyanide all of AR grade were obtained from M/s s. d. Fine chemical Pvt. Ltd. Mumbai, India. All phase transfer catalysts used in this work were received as gift samples from M/s Dishman Pharmaceuticals and Chemicals Ltd., Ahmedabad, India.

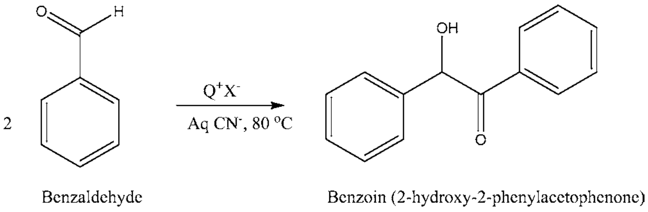
2.2. Experimental Setup. The reactions were studied in a 5.0 cm i.d. fully baffled mechanically agitated contactor of 100 cm^3 total capacity, which was equipped with a six-blade-turbine impeller (1.7 cm diameter) and a reflux condenser. The reactor was kept in an isothermal bath whose temperature could be maintained at the desired value using a temperature indicator controller. Typical runs were conducted by taking 0.012 mol of benzaldehyde and 0.2 cm^3 of *n*-dodecane as an internal standard, and total volume was made up to 10 cm^3 with toluene. The aqueous phase was composed of 0.005 mol of sodium cyanide dissolved in water to make up to 10 cm^3. Both organic and aqueous phases were added to the reactor, and 0.003 mol of quaternary ammonium salt was then added after the temperature reached the set value. All typical reactions were carried out at 80 °C and 900 rpm. All experiments were repeated thrice, and the average values were taken for studying the effects of different parameters on conversions and rates.

2.3. Analysis. Samples were withdrawn periodically and analysed by gas chromatography (Chemito Model GC-1000, FID detector) using capillary column BP-1, (0.25 mm × 30 m). Calibration was done by synthetic mixtures and used for quantification. The products were also confirmed by GC–MS. (Perkin-Elemer Clarius Model 500) by using a BPX-1 capillary column (250 mm × 30 m) packed with methyl polysiloxane.

3. RESULTS AND DISCUSSION

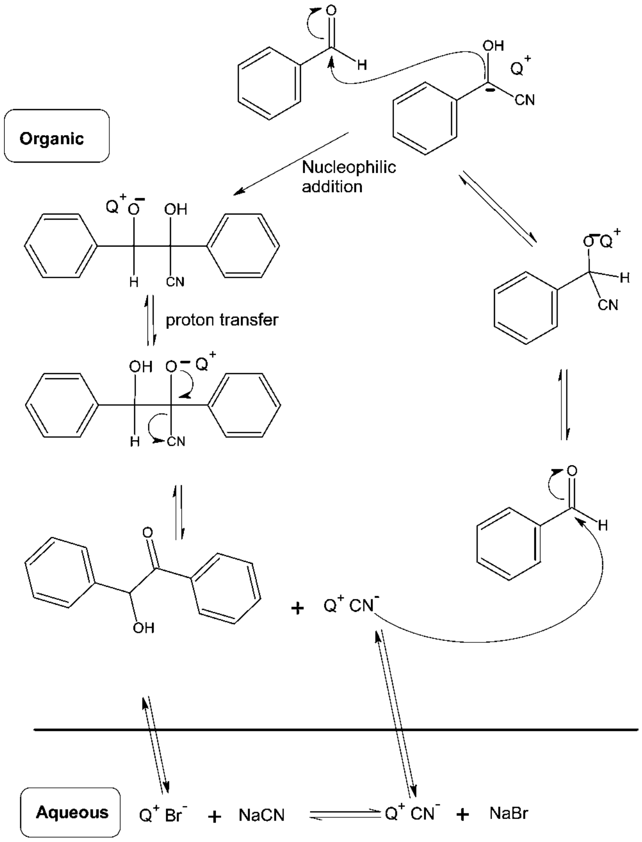
The overall liquid–liquid reaction is given by Scheme 1.

Scheme 1. Benzoin Condensation Reaction



The mechanism of this reaction is given by Scheme 2. It is derived from the classical mechanism given by Lapworth for benzoin condensation.[24] In this mechanism, first anion (X^-) of the added quaternary ammonium salt (Q^+X^-) undergoes equilibrium exchange reaction to form an ion pair (Q^+CN^-) with the CN^- anion of NaCN. This ion pair is then transferred across the aqueous–organic interface. In the organic phase, Q^+CN^- reacts with one aldehyde molecule in nucleophilic addition on the carbonyl carbon to form an intermediate. Rearrangement of the intermediate results in polarity reversal at the carbonyl carbon, and the electrophilic aldehyde carbon becomes nucleophilic after deprotonation. This carbanion thereafter adds to the second aldehyde molecule in nucleophilic addition, which is followed by quick proton transfer and elimination of the cyanide ion as ion pair to give benzoin as the product. The ion pair Q^+CN^- is regenerated and is available for the next catalytic cycle.

Scheme 2. Proposed Reaction Mechanism for Benzoin Condensation: A Case of Pseudo-Phase Transfer Catalysis (PTC)



The cyanide ion serves three different purposes in the course of this reaction. It acts as a nucleophile, facilitates proton abstraction, and is also the leaving group in the final step. The benzoin condensation is really a dimerization and not a condensation because water is not released in this reaction. For this reason the reaction is also called a benzoin addition. In this reaction, the two aldehydes serve different purposes; one aldehyde donates a proton, and one aldehyde accepts a proton. The Q^+ serves the purpose of forming an ion pair with the organic moiety with a negative charge on it.

3.1. Kinetic Modeling. The benzoin (P) formation from condensation (dimerization) of two molecules of benzaldehyde is a 100% atom economical reaction that is accelerated by metal cyanide as catalyst in a two-phase system. Indeed, this reaction has been studied in a homogeneous reaction using alcohols as solvent.[25] According to this report, the reaction is kinetically second order in benzaldehyde and first order in cyanide ion. In the current studies, it was thought worthwhile to use the typical phase transfer catalyst as a "co-catalyst". Preliminary studies indicated that the rates of reaction are much enhanced by addition of a quaternary salt, which is typically used as a phase transfer catalyst (Q^+X^-). However, there is a subtle difference in the mechanism, and there is no formal transfer of any anion across the liquid–liquid interface as is typically the case for PTC reaction. The following exchange reaction take places in the aqueous phase:

$$\mathrm{MCN(aq) + QX(aq) \rightarrow QCN(aq) + MX(aq)} \qquad (1)$$

which is given by the following exchange equilibrium:

$$[\mathrm{Q^+X^-}]_{\mathrm{aq}} + [\mathrm{M^+CN^-}]_{\mathrm{aq}} \overset{K_1}{\rightleftarrows} [\mathrm{Q^+CN^-}]_{\mathrm{aq}} + [\mathrm{M^+X^-}]_{\mathrm{aq}} \tag{2}$$

$$K_1 = \frac{[\mathrm{Q^+CN^-}]_{\mathrm{aq}}[\mathrm{M^+X^-}]_{\mathrm{aq}}}{[\mathrm{Q^+X^-}]_{\mathrm{aq}}[\mathrm{M^+CN^-}]_{\mathrm{aq}}} = \frac{[\mathrm{Q^+CN^-}]_{\mathrm{aq}}[\mathrm{X^-}]_{\mathrm{aq}}}{[\mathrm{Q^+X^-}]_{\mathrm{aq}}[\mathrm{CN^-}]_{\mathrm{aq}}} \tag{3}$$

There is a distribution of ion pair $\mathrm{Q^+CN^-}$ between the two phases:

$$[\mathrm{Q^+CN^-}]_{\mathrm{aq}} \overset{K_2}{\rightleftarrows} [\mathrm{Q^+CN^-}]_{\mathrm{org}} \tag{4}$$

$$K_2 = \frac{[\mathrm{Q^+CN^-}]_{\mathrm{org}}}{[\mathrm{Q^+CN^-}]_{\mathrm{aq}}} \tag{5}$$

$$[\mathrm{Q^+CN^-}]_{\mathrm{org}} = \frac{K_1K_2[\mathrm{Q^+X^-}]_{\mathrm{aq}}[\mathrm{CN^-}]_{\mathrm{aq}}}{[\mathrm{X^-}]_{\mathrm{aq}}} \tag{6}$$

The substrate A reacts with $[\mathrm{Q^+CN^-}]_{\mathrm{org}}$ according to

$$\mathrm{A}_{\mathrm{org}} + [\mathrm{Q^+CN^-}]_{\mathrm{org}} \overset{K_3}{\rightleftarrows} [\mathrm{Q^+ACN^-}]_{\mathrm{org}} \tag{7}$$

$$K_3 = \frac{[\mathrm{Q^+ACN^-}]_{\mathrm{org}}}{[\mathrm{A}]_{\mathrm{org}}[\mathrm{Q^+CN^-}]_{\mathrm{org}}} \tag{8}$$

This is an intermediate that condenses with A in a subsequent step as per the following:

$$\mathrm{A}_{\mathrm{org}} + [\mathrm{Q^+ACN^-}]_{\mathrm{org}} \overset{K_4}{\rightleftarrows} [\mathrm{PQ^+CN^-}]_{\mathrm{org}} \tag{9}$$

$$K_4 = \frac{[\mathrm{PQ^+CN^-}]_{\mathrm{org}}}{[\mathrm{A}]_{\mathrm{org}}[\mathrm{Q^+ACN^-}]_{\mathrm{org}}} \tag{10}$$

The final product is obtained as

$$[\mathrm{PQ^+CN^-}]_{\mathrm{org}} \xrightarrow{k_r} \mathrm{P}_{\mathrm{org}} + [\mathrm{Q^+CN^-}]_{\mathrm{org}} \tag{11}$$

The rate of formation of P is equal to the rate of reaction of the intermediate $[\mathrm{PQ^+CN^-}]_{\mathrm{org}}$ (eq 11), provided it is the rate-determining step:

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{P}]_{\mathrm{org}}}{\mathrm{d}t} &= \frac{-\mathrm{d}[\mathrm{PQ^+CN^-}]_{\mathrm{org}}}{\mathrm{d}t} = k_r[\mathrm{PQ^+CN^-}]_{\mathrm{org}}\\ &= k_rK_4[\mathrm{A}]_{\mathrm{org}}[\mathrm{Q^+ACN^-}]_{\mathrm{org}}\\ &= k_rK_4K_3[\mathrm{A}]^2_{\mathrm{org}}[\mathrm{Q^+CN^-}]_{\mathrm{org}}\\ &= \frac{k_rK_4K_3K_2K_1[\mathrm{A}]^2_{\mathrm{org}}[\mathrm{Q^+X^-}]_{\mathrm{aq}}[\mathrm{CN^-}]_{\mathrm{aq}}}{[\mathrm{X^-}]_{\mathrm{aq}}}\end{aligned} \tag{12}$$

The catalyst is distributed as two ions pairs in each of the organic and aqueous phases. If N_{Q} is total amount of catalyst (mol) added to the reaction mixture initially and ϕ is the fraction of the catalyst cation $\mathrm{Q^+}$ distributed in the organic (reaction) phase, then

$$[\mathrm{Q^+X^-}]_{\mathrm{org}}V_{\mathrm{org}} + [\mathrm{Q^+CN^-}]_{\mathrm{org}}V_{\mathrm{org}} = \phi N_{\mathrm{Q}} \tag{13}$$

$$[\mathrm{Q^+X^-}]_{\mathrm{aq}}V_{\mathrm{aq}} + [\mathrm{Q^+CN^-}]_{\mathrm{aq}}V_{\mathrm{aq}} = (1-\phi)N_{\mathrm{Q}} \tag{14}$$

Also

$$K_5 = \frac{[\mathrm{Q^+X^-}]_{\mathrm{org}}}{[\mathrm{Q^+X^-}]_{\mathrm{aq}}} \tag{15}$$

$$\begin{aligned}[\mathrm{Q^+CN^-}]_{\mathrm{org}} &= \phi\frac{N_{\mathrm{Q}}}{V_{\mathrm{org}}} - [\mathrm{Q^+X^-}]_{\mathrm{org}}\\ &= \phi\frac{N_{\mathrm{Q}}}{V_{\mathrm{org}}} - K_5[\mathrm{Q^+X^-}]_{\mathrm{aq}}\\ &= \phi\frac{N_{\mathrm{Q}}}{V_{\mathrm{org}}} - K_5\left\{\frac{(1-\phi)N_{\mathrm{Q}}}{V_{\mathrm{aq}}} - [\mathrm{Q^+CN^-}]_{\mathrm{aq}}\right\}\\ &= \phi\frac{N_{\mathrm{Q}}}{V_{\mathrm{org}}} - K_5\left\{\frac{(1-\phi)N_{\mathrm{Q}}}{V_{\mathrm{aq}}} - \frac{[\mathrm{Q^+CN^-}]_{\mathrm{org}}}{K_2}\right\}\end{aligned} \tag{16}$$

$$\begin{aligned}[\mathrm{Q^+CN^-}]_{\mathrm{org}} &= \frac{N_{\mathrm{Q}}\left[\phi\left(\frac{1}{V_{\mathrm{org}}} + \frac{K_5}{V_{\mathrm{aq}}}\right) - \frac{K_5}{V_{\mathrm{aq}}}\right]}{\left(1 - \frac{K_5}{K_2}\right)}\\ &= \psi N_{\mathrm{Q}}\end{aligned} \tag{17}$$

Equation 17 shows that a fixed quantity of catalyst exists in the organic phase and there is no phase transfer of the anions across the interface as it happens in the usual PTC.

Equation 12 can thus be written as

$$\frac{\mathrm{d}[\mathrm{P}]_{\mathrm{org}}}{\mathrm{d}t} = \frac{-\mathrm{d}[\mathrm{PQ^+CN^-}]_{\mathrm{org}}}{\mathrm{d}t} = k_rK_4K_3[\mathrm{A}]^2_{\mathrm{org}}\psi N_{\mathrm{Q}} \tag{18}$$

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{P}]_{\mathrm{org}}}{\mathrm{d}t} &= \frac{-\mathrm{d}[\mathrm{PQ^+CN^-}]_{\mathrm{org}}}{\mathrm{d}t}\\ &= \frac{1}{2}\frac{-\mathrm{d}[\mathrm{A}]_{\mathrm{org}}}{\mathrm{d}t}\\ &= k_rK_4K_3\psi[\mathrm{A}]^2_{\mathrm{org}}N_{\mathrm{Q}}\end{aligned} \tag{19}$$

$$\frac{-\mathrm{d}[\mathrm{A}]_{\mathrm{org}}}{\mathrm{d}t} = 2k_rK_4K_3\psi[\mathrm{A}]^2_{\mathrm{org}}N_{\mathrm{Q}} \tag{20}$$

The above equation can be written in terms of fractional conversion of A:

$$\frac{\mathrm{d}X_{\mathrm{A}}}{\mathrm{d}t} = k_p[\mathrm{A_0}]_{\mathrm{org}}(1 - X_{\mathrm{A}})^2N_{\mathrm{Q}} \tag{21}$$

where $[\mathrm{A_0}]$ is the initial concentration of A and X_{A} is the fractional conversion.

$$k_p = 2k_rK_4K_3\psi \tag{22}$$

Equation 21 can be integrated to get the following for a given catalyst concentration:

$$\frac{X_{\mathrm{A}}}{(1 - X_{\mathrm{A}})} = k_p[\mathrm{A_0}]_{\mathrm{org}}N_{\mathrm{Q}}t = k_2t \tag{23}$$

If a plot of $X_A/(1 - X_A)$ versus t is made, it will give a slope equal to k_2 from which k_p can be calculated

On the contrary if the formation of the intermediate given by eq 7 is the rate-determining step, then it becomes a first order reaction leading to the following:

$$-(1 - X_A) = k_A N_Q t = k_1 t \tag{24}$$

In such a case all subsequent steps are very fast. In both of the above cases, the order in Q^+CN^- is first order. So for a fixed benzaldehyde concentration, the initial rate of reaction will be first order in Q^+CN^-. In other words, plots of k_2 or k_1 can be made for different concentrations of the initial amount of N_Q to find a linear dependence on N_Q.

3.2. Effect of Speed of Agitation. The above theoretical analysis suggested that the formation of the ion pair Q^+CN^- in the aqueous phase and its transfer to the organic phase will not be a rate-determining step if the equilibrium of the exchange reaction given by eq 2 is shifted to the right. Therefore the amount of NaCN was taken in large excess over the quaternary salt in order to convert it into Q^+CN^-. Thus, to ascertain the influence of external mass transfer resistance on reaction rate, the effect of speed of agitation was studied from 700 to 1000 rpm (Figure.1) under otherwise similar conditions in the presence of tetrabutylammonium bromide (TBAB). The conversion was found to be practically same at 900 and 1000 rpm. This would facilitate that the formation and transfer of Q^+CN^-. Further increase in speed of agitation had practically no effect on conversion; hence all further studies were carried out at 900 rpm.

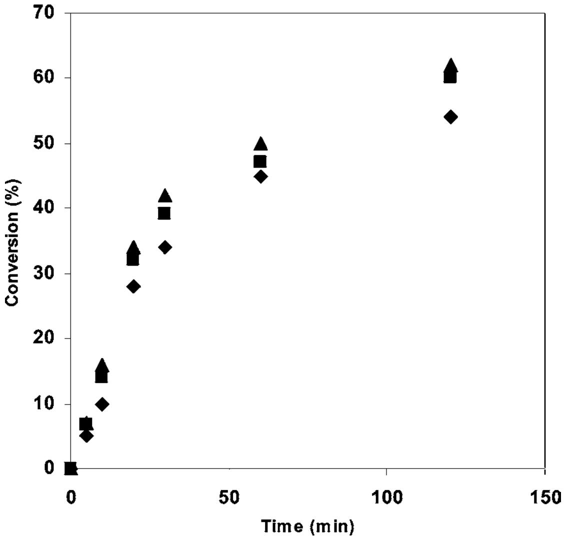


Figure 1. Effect of speed of agitation. Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, NaCN 0.005 mol, TBAB 0.003 mol, toluene 10 cm^3, water 10 cm^3, temperature 80 °C. (♦) 700 rpm, (■) 900 rpm, (▲) 1000 rpm.

3.3. Effect of Various Catalysts. The effect of various catalysts such as tetra-*n*-butylammonium bromide (TBAB), tetramethylammonium bromide (TMAB), ethyltriphenylphosphonium bromide (ETPB), and tetrabutylammonium hydrogensulfate (TBAHS) was studied under otherwise similar reaction conditions (Figure 2). The order of activity was as follows:

TBAB > TBAHS > TMAB > ETPB

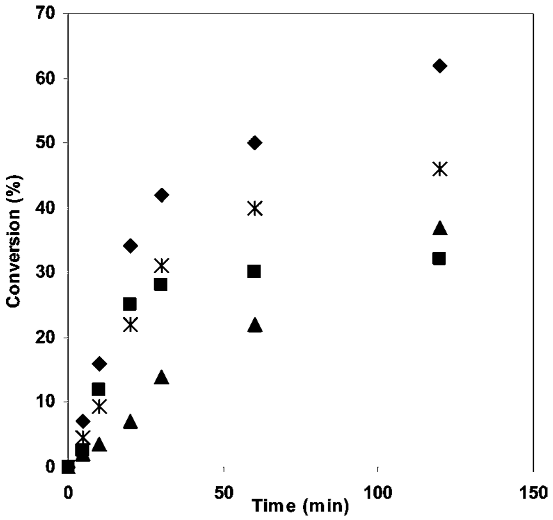


Figure 2. Effect of various catalysts. Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, NaCN 0.005 mol, catalyst loading 0.003 mol, toluene 10 cm^3, water 10 cm^3, temperature 80 °C, speed of agitation 900 rpm. (♦) TBAB, (∗) TBAHS, (■) TMAB, (▲) ETPB.

It was observed that out of these TBAB gave the highest reaction rate and maximum conversion. The ability of the quaternary salt to catalyze this reaction effectively depended on how easily the ion pair was formed and the cyanide ion was transported from the aqueous phase to the organic phase. In other words, the distribution constant given by K_2 as well as the basicity of Q^+CN^- should dictate the efficacy of a given catalyst. ETPB showed the least activity; this might be because of the presence of bulky phenyl groups on the ammonium cation, which does not have good solubility or distribution of the ion pair Q^+CN^- in the organic phase, or its basicity is the least. It appears that the formation of ETP^+CN^- is not as efficient as others, and thus there is less concentration of this ion pair in the organic phase, making it a poor catalyst. TMAB showed fairly good activity, but because of its smaller methyl group it concentrated mostly in aqueous phase and hence had a lesser distribution in the organic phase. Out of the remaining two (i.e., TBAB and TBAHS) TBAB showed good activity and hence was selected for further studies. In the case of TBAHS, the formation of TBA^+CN^- is not as efficient as it would be from TBAB. Thus, the model as given by eq 23 was fitted for each catalyst (Figure 3).

The k_p values in s^{-1} cm^3 mol^{-2} for each catalyst are in the following order:

$$\begin{aligned} \text{TBAB}(111.1) &> \text{TBAHS}(68.5) \\ &> \text{TMAB}(64.8) \\ &> \text{ETPB}(22.2) \end{aligned}$$

These values support the arguments advanced in the foregoing discussion.

3.4. Effect of Catalyst (TBAB) Concentration. TBAB concentration was varied from 1.5×10^{-4} to 3.0×10^{-4} mol cm^{-3} of the total reaction volume (Figure 4). With increasing catalyst concentration, there was increase in the conversion, which is as per eq 23. Practically the same conversion was obtained for 2.5×10^{-4} and 3.0×10^{-4} mol cm^{-3}catalyst since the effective concentration of Q^+CN^- in the organic phase was almost the same. The concentration of TBAB was also

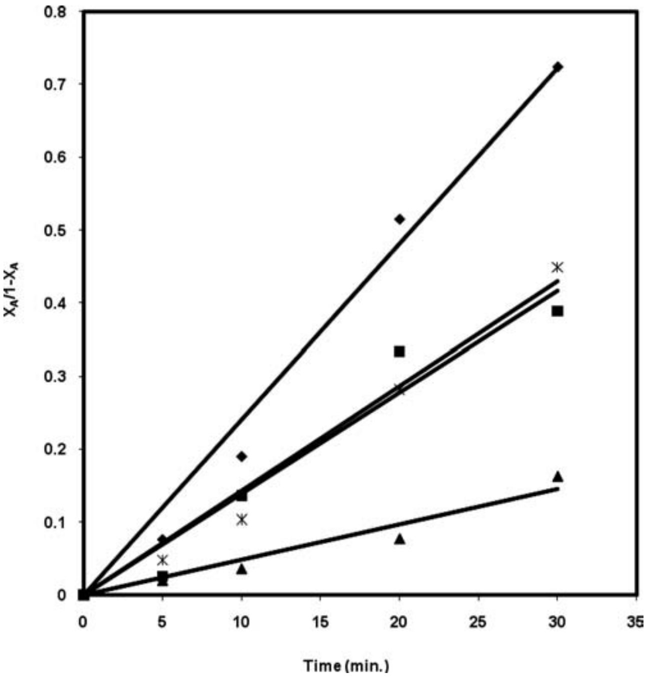


Figure 3. Model fitting for different catalysts. Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, NaCN 0.005 mol, catalyst loading 0.003 mol, toluene 10 cm^3, water 10 cm^3, temperature 80 °C, speed of agitation 900 rpm. (♦) TBAB, (∗) TBAHS, (■) TMAB, (▲) ETPB.

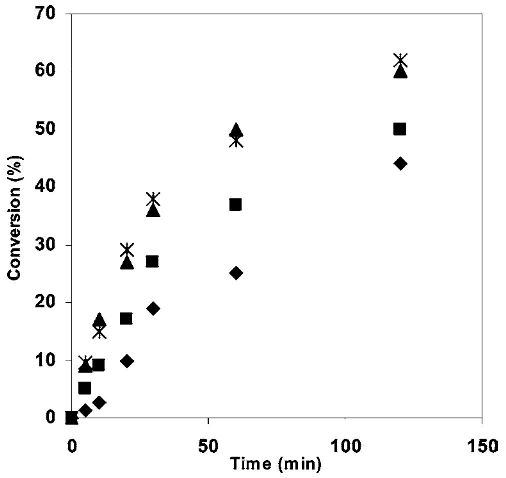


Figure 4. Effect of TBAB concentration (mol cm^{-3}). Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, NaCN 0.005 mol, toluene 10 cm^3, water 10 cm^3, temperature 80 °C, speed of agitation 900 rpm. (♦) 1.5 × 10^{-4}, (■) 2.0 × 10^{-4}, (▲) 2.5 × 10^{-4}, (∗) 3.0 × 10^{-4}, (●) 1.0 × 10^{-3}.

increased to 1.0 × 10^{-3} to find that practically the same conversion was obtained since the effective concentration of Q^+CN^- in the organic phase was almost the same. So increasing the concentration of TBAB was of no use.

Thus, the initial rate of reaction was plotted against N_Q to obtain a linear dependence on it (Figure 5). This also demonstrates the validity of the model. Hence all further reactions were done using 2.5 × 10^{-4} mol cm^{-3} catalyst concentration.

3.5. Effect of Phase Volume Ratio.

The effect of phase volume ratio of organic phase to aqueous phase was studied for 1:0.5, 1:1, and 0.5:1 ratios under otherwise similar reaction conditions. The moles of all the reactants and catalyst were also kept constant (Figure 6). When the phase volume ratio was taken as 0.5:1, the conversion was higher than that for 1:1; this might be because of increase in concentration of Q^+CN^- in the organic phase, which leads to increase in reaction rate. This is also seen in the definition of the constant ψ, which increases when the organic phase volume is less. Also concentration of reactant aldehyde increases in less organic volume. For the phase volume ratio of 1:0.5 high conversion was obtained compared to that for 1:1, but selectivity for benzoin was less. The model was fitted for different phase volume ratios as given in Figure 7. It suggests that the assumptions made are valid for this model.

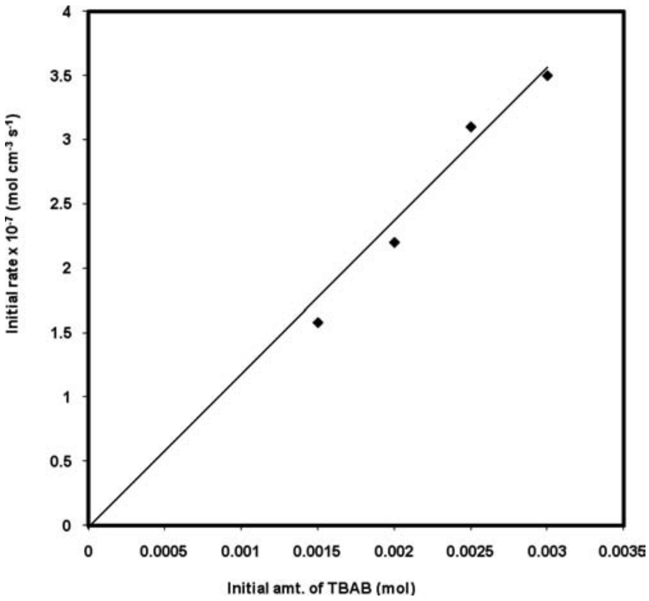


Figure 5. Plot of initial rate versus initial amount of TBAB (N_Q). Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, NaCN 0.005 mol, toluene 10 cm^3, water 10 cm^3, temperature 80 °C, speed of agitation 900 rpm.

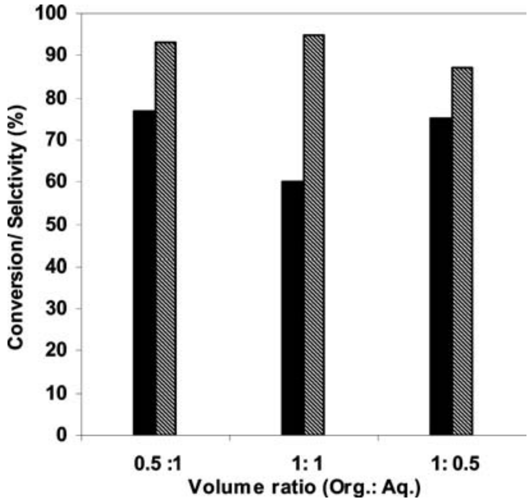


Figure 6. Effect of phase volume ratio. Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, NaCN 0.005 mol, TBAB loading 0.0025 mol, temperature 80 °C, speed of agitation 900 rpm. (black bar) Conversion. (hashed bar) Selectivity.

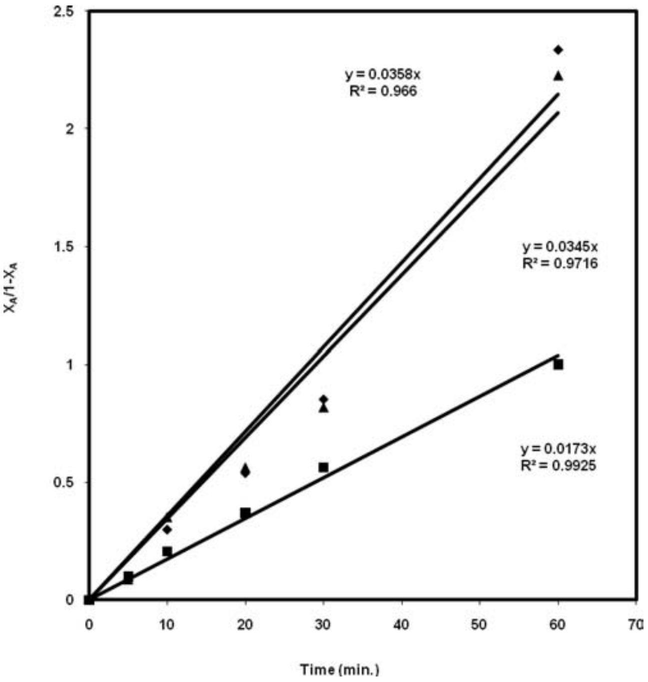


Figure 7. Model fitting for different phase volume ratio (org:aq) (♦) 0.5:1, (■) 1:1, (▲) 1:0.5.

3.6. Effect of Sodium Cyanide (NaCN) Concentration.

Effect of NaCN concentration was studied in the range of 2.5 × 10^{-4} to 7.5 × 10^{-4} mol cm^{-3} of the aqueous phase (Figure 8).

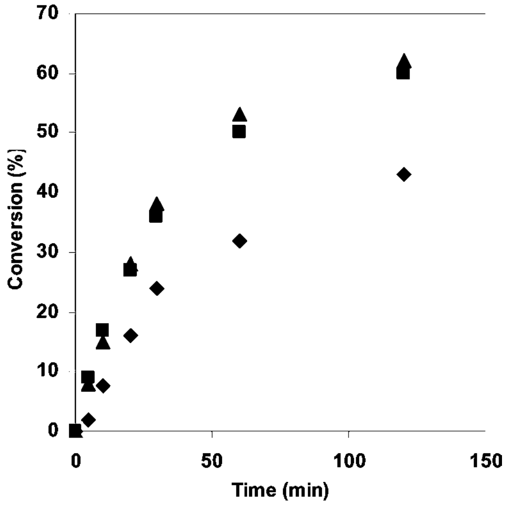


Figure 8. Effect of NaCN concentration (mol cm^{-3}). Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, TBAB 0.0025 mol, toluene 10 cm^3, water 10 cm^3, temperature 80 °C, speed of agitation 900 rpm. (♦) 2.5 × 10^{-4}, (■) 5.0 × 10^{-4}, (▲) 7.5 × 10^{-4}.

It was observed that rate of reaction as well as total conversion increased for NaCN loading of 5.0 × 10^{-4} mol cm^{-3} compared to that for 2.5 × 10^{-4} mol cm^{-3}. This is also reflected in the formation of higher concentration of Q^+CN^- as given by eq 2. Conversion was found to be practically the same for NaCN concentrations of 5.0 × 10^{-4} and 7.5 × 10^{-4} mol cm^{-3} because all TBAB was converted into Q^+CN^- at both these concentrations and thus the effective concentration of Q^+CN^- in the organic phase was the same. Hence all further studies were done at NaCN concentration of 5.0 × 10^{-4} mol cm^{-3}.

3.7. Effect of Benzaldehyde Concentration.

The concentration of benzaldehyde was varied from 1.0 × 10^{-3} to 1.4 × 10^{-3} mol cm^{-3} of organic phase (Figure 9). As expected, it was observed that as the concentration of benzaldehyde increases, the rate of reaction as well as overall conversion increases. The second order model was also found to fit the data well (Figure 10).

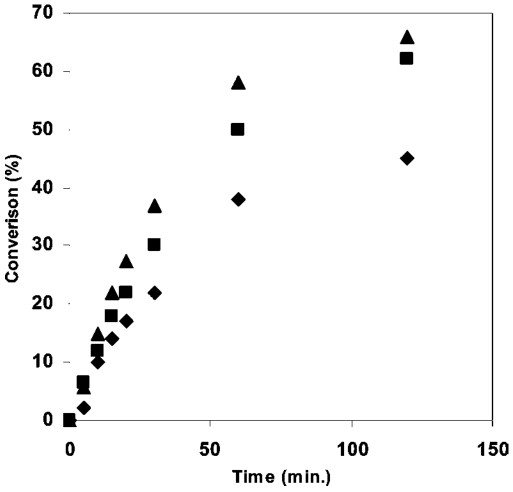


Figure 9. Effect of benzaldehyde concentration (mol cm^{-3}). *n*-Dodecane 0.2 cm^3, TBAB 0.0025 mol, toluene 10 cm^3, NaCN 0.005 mol, water 10 cm^3, temperature 80 °C, speed of agitation 900 rpm. (♦) 1.0 × 10^{-3}, (■) 1.2 × 10^{-3}, (▲) 1.4 × 10^{-3}.

3.8. Effect of Temperature.

Effect of temperature on the reaction rate was studied in the range of 70–90 °C (Figure.11). It was observed that as the temperature increased, the rate of

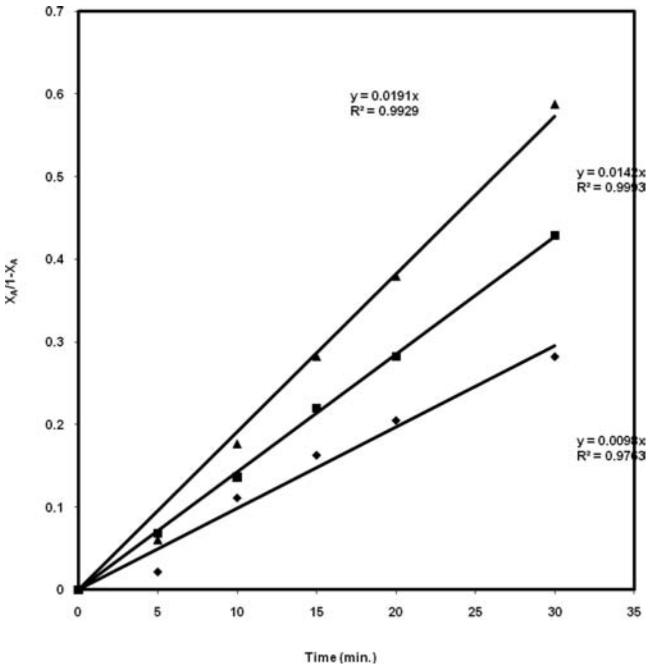


Figure 10. Validation of the model for different benzaldehye concentration (mol cm^{-3}). (♦) 1.0 × 10^{-3}, (■) 1.2 × 10^{-3}, (▲) 1.4 × 10^{-3}.

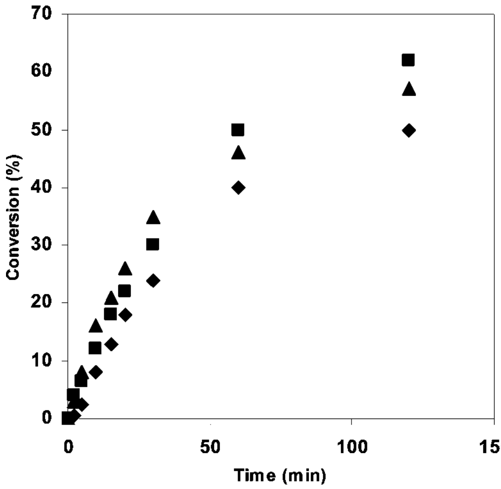


Figure 11. Effect of temperature (°C). Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, TBAB 0.0025 mol, toluene 10 cm^3, NaCN 0.005 mol, water 10 cm^3, speed of agitation 900 rpm. (◆) 70, (■) 80, (▲) 90.

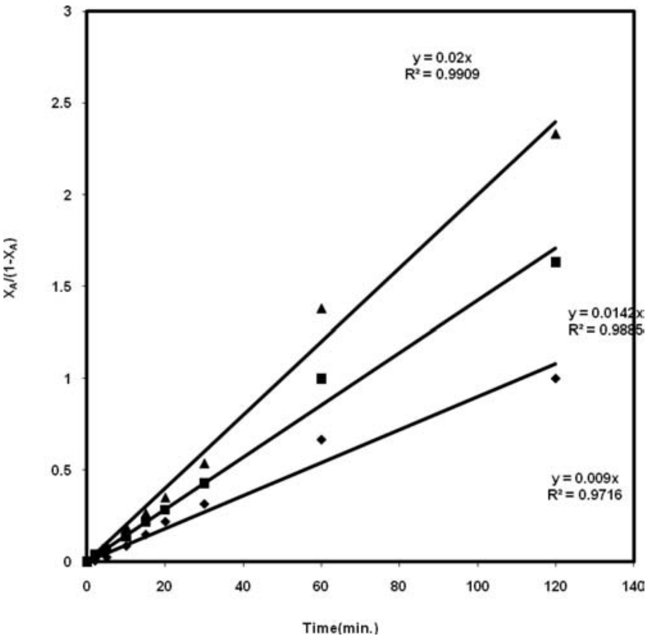


Figure 12. Model validation for different temperature (°C). (◆) 70, (■) 80, (▲) 90.

reaction increased; hence this showed that reaction was basically kinetically controlled. Thus plots of $(X_A)/(1 - X_A)$ versus *t* were made at different temperatures (Figure 12). The slopes equal to k_2 were calculated. Arrhenius plots of ln k_2 versus $1/T$ (K^{-1}) were made (Figure 13) to obtain the activation energy as 9.85 kcal mol^{-1}. Activation energy values for heterogeneous liquid–liquid system below 4.0 kcal mol^{-1} would suggest mass transfer resistance. This also shows that the reaction is intrinsically kinetically controlled and occurs in a single phase. There is no question of mass transfer resistance here since there was no transfer of ion pair once it is transferred to the organic phase.

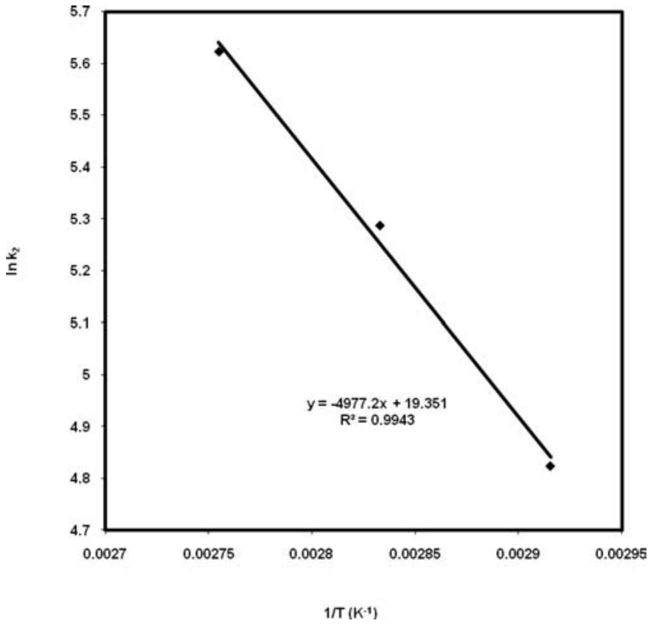


Figure 13. Arrhenius plot.

3.9. Aqueous Phase Reusability. After the reaction was completed, the aqueous phase was separated through a separation funnel. To that was added a fresh batch of toluene and benzaldehyde, and the reaction was carried out at 80 °C. The results are given in Figure 14. It was observed that, without addition of fresh catalyst or sodium cyanide, the reaction proceeded to large extent. This showed that the aqueous phase can be reused very conveniently. The small decrease in activity might be due to loss of TBAB in the organic phase. In order to verify these findings the model was fitted. The second order constant k_2 was calculated and was used to compare against N_Q. This shows the effective concentration of the catalyst that remained in the aqueous phase. It suggested that ~38% of catalyst was lost in the organic phase during the first use and ~56% of the initial quantity was lost after the second use. This is the most interesting feature of the study; normally the aqueous phase is not used in L–L PTC reactions.

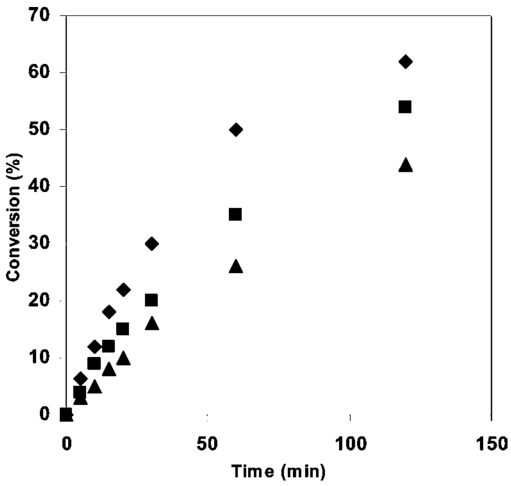


Figure 14. Aqueous phase reusability. Benzaldehyde 0.012 mol, *n*-dodecane 0.2 cm^3, toluene 10 cm^3, aqueous phase 10 cm^3, speed of agitation 900 rpm. (◆) Fresh use, (■) 1st reuse, (▲) 2nd reuse.

4. CONCLUSIONS

The benzoin condensation reaction was studied systematically by using the typical quaternary ammonium salts in conjunction with NaCN in a liquid−liquid system. The effects of various parameters on the conversion and rates of reaction were studied. A mechanistic model was built, and the kinetics was deduced and verified against the experimental data. Although the quaternary salts are a co-catalyst, during the reaction catalyst is the partitioned quaternary cyanide ion pair, which is distributed in the organic phase. Then it participates in the reaction and forms the first intermediate, which then dimerises with benzaldehyde. There is a fixed concentration of the Q^+CN^- ion pair in the organic phase, which is the true catalyst, and there is no transfer of ions across the interface. The distribution and basicity of the ion pair in abstracting a proton from benzaldehyde decide the efficacy of the catalyst. It was also found that the aqueous phase can be reused by replacing the organic phase. This is because there is still sufficient quantity of Q^+CN^- left in the aqueous phase. This may be termed as pseudo-phase transfer catalysis. This is the first example of its kind being reported in the literature.

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Notes

The authors declare no competing financial interest.

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■ NOMENCLATURE

$[A]_{org}$ = concentration of benzaldehyde in the organic phase, mol/cm^3

k_{org} = second order rate constant of forward reaction in organic phase cm^3/mol·s

K_1 = equilibrium constant for anion exchange in aqueous phase

K_2 = distribution constant for ion pair Q^+CN^- between organic and aqueous phase

K_3 = equilibrium constant for organic phase reaction of A with Q^+CN^-

K_4 = equilibrium constant for organic phase reaction of A with intermediate Q^+ACN^-

N_Q = total moles of catalyst added to the system at time t = 0, mol

$[N_Q]_{org}$ = moles of catalyst in the organic phase, mol

$[Q^+X^-]_{org}$ = concentration of quaternary salt in the organic phase, mol/cm^3

$[Q^+X^-]_{aq}$ = concentration of quaternary salt in the aqueous phase, mol/cm^3

$[Q^+CN^-]_{aq}$ = concentration of Q^+CN^- ion pair in the aqueous phase, mol/cm^3

$[Q^+CN^-]_{org}$ = concentration of Q^+CN^- ion pair in the organic phase, mol/cm^3

T = temperature, K

V_{aq} = volume of the aqueous phase, cm^3

V_{org} = volume of the organic phase, cm^3

X_A = fractional conversion of reactant A

ψ = fraction of quaternary cation in the organic phase

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