



# Catalytic esterification of sodium salicylate in third-liquid phase under ultrasound-assisted tri-liquid phase-transfer catalysis

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## ABSTRACT

The esterification of sodium salicylate to synthesize *n*-butyl salicylate was investigated via ultrasound-assisted tri-liquid phase-transfer catalysis. The third-liquid phase containing the catalytic intermediate tetra-*n*-butylphosphonium salicylate (ArCOOQ) was prepared from the reaction of sodium salicylate and tetra-*n*-butylphosphonium bromide with a large excess of NaBr in the aqueous phase. Under ultrasonic irradiation at 28 kHz/300 W, the product yield in the organic phase was 97.4% at 70 °C after 100 min of reaction in a batch reactor. The reaction rate increased with decreasing ultrasonic frequency in the range of 28–80 kHz. The variations of ArCOOQ in the third-liquid phase during reaction were analyzed. A pseudo-first-order kinetic model was proposed to describe the overall reaction. The increment in apparent rate constant was 53.3% under ultrasonic irradiation. The assistance of ultrasound in third-liquid phase-transfer catalysis provides an efficient and environmentally benign method to synthesize esters.

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## 1. Introduction

Phase-transfer catalysis is a powerful technique to conduct the reactions between two mutually insoluble reactants, and has been widely applied in the synthesis of fine chemicals including pharmaceuticals, flavors, dyes, perfumes, etc. [1]. For phase-transfer catalyzed systems under some critical conditions, the catalyst and active catalytic intermediate would be highly concentrated within a viscous thin layer between the aqueous and organic phases. This thin layer, the “third-liquid” phase with the characteristics between hydrophilic and hydrophobic properties, usually catalyzes the reaction in a high conversion and selectivity at mild conditions. This type of reaction is called the third-liquid phase-transfer catalysis (TLPTC). For such a tri-liquid system, the separation of products and catalyst recovery are relatively easier than a liquid–liquid system. Without using aprotic or halide-containing solvents and with high catalytic efficiency, TLPTC is regarded as a green technology in organic synthesis [2].

In 1984, Neumann and Sasson investigated the isomerization of allylanisole using polyethylene glycol as the catalyst in a toluene and aqueous KOH solution. They observed a high activity third-liquid phase formed between the aqueous and the organic phases [3]. Later, Wang and Weng performed the reaction of benzyl chloride and sodium bromide using tetra-*n*-butylammonium bromide as the catalyst in a liquid–liquid system. They found that the

reaction rate rapidly increased as the catalyst employed over a certain amount, forming a third-liquid phase [4]. The formation of third-liquid phase is subjected to the interaction of phase-transfer catalyst, molecular structure of reactants, inorganic salts, and organic solvents [5,6]. The main reaction zone for TLPTC is the third-liquid phase which mainly contains the catalyst and catalytic intermediate [7]. The catalytic intermediate reacts with the organic reactant that is transferred across the interface between organic phase and third-liquid phase. The interfacial characteristics thus play important role in TLPTC. The interfacial tension for the organic/third-liquid interface was less than that for the aqueous/third-liquid interface, which contributed to the faster reaction of organic substrate with the catalytic intermediate in the third-liquid phase [8]. Further, Huang and Yang reported that the reaction rate of the benzylation of sodium 4-acetylphenoxide in a third-liquid phase-transfer catalyzed system was faster than that conducted in a liquid–liquid PTC system by 25–28 times and the concentration of catalytic intermediate in the third-liquid phase slightly decreased with increasing reaction time [9]. The molecular structure may influence the reaction regime. For a catalytic benzylation of sodium 4-chloro-3-methylphenoxide system, the reaction rate is strongly dependent on the stirring speed, showing that the interfacial reaction is important. The molar ratio of catalytic intermediate in the third-liquid phase remains almost constant after 2 min of reaction [10].

In general, third-liquid phase-transfer catalysis shows a great enhancement in reaction rate compared to the liquid–liquid PTC. Recently, ultrasound or microwave activation combined with phase-transfer catalysis has attracted considerable interests [11].

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When the ultrasonic wave propagates in a liquid solution, the alternate compression and depression are produced to form cavities within which temperature and pressure can reach 5000 K and several hundred bars. The reaction rate is thus enhanced. Entezari and Shameli studied the effect of an ultrasonic wave on the Cannizzaro reaction catalyzed by a phase-transfer catalyst. Their results showed that an ultrasonic wave of 20 kHz dramatically accelerates on the reaction [12]. Wang and Rajendran explored the effect of ultrasound on the liquid–liquid phase-transfer catalyzed epoxidation and dichlorocyclopropanation of 1,7-octadiene. They found that the reaction rates were greatly enhanced by the assistance of ultrasound, either in epoxidation by using Aliquat 336/cocatalyst phosphotungstic acid or in dichlorocyclopropanation by using benzyltriethylammonium chloride as the catalyst [13,14]. Li and Li investigated the reaction of oximes and dichloromethane catalyzed by NaOH and phase-transfer catalyst under the assistance of ultrasound. The product yield of 95% in 3.5 h of reaction was obtained using ultrasound, while it needed 16 h of reaction to attain 92% of product yield in the silence condition [15]. Nandurkar et al. studied the selective nitration of phenols and found that the rate was enhanced using dilute nitric acid (6 wt%)/tetra butyl ammonium bromide (TBAB) under sonication [16].

In the past efforts, ultrasound irradiation were commonly employed in two-liquid phase-transfer catalysis and showed a significant enhancement in reaction rate. In the present study, the aim is to develop an effective method by applying ultrasound in a third-liquid phase to conduct the catalyzed esterification of sodium salicylate with *n*-butyl bromide under tri-liquid phase-transfer catalysis. The reaction mechanism and the kinetic model were proposed to describe the reaction rate. The catalytic behaviors of catalytic intermediate in the third-liquid phase under ultrasonic irradiation were analyzed.

## 2. Experimental

Reagent sodium salicylate (ArCOONa, 99.5+%) from SHOWA was used as the aqueous reactant without further treatment. Tetra-*n*-butylphosphonium bromide (TBPB or QBr in general), *n*-butyl bromide (RBr), the desired product *n*-butyl salicylate (ArCOOR), and other reagents are all reagent-grade chemicals from SHOWA, ACROS, TEDIA, Lancaster and TCI.

### 2.1. Synthesis of tetrabutylphosphonium salicylate and formation of third-liquid phase

A definite amount of TBPB and excess ArCOONa were introduced into 20 cm<sup>3</sup> of de-ionized and shaken at 70 °C for 1 h to produce ArCOOQ. ArCOOQ in the aqueous solution was then extracted with 20 cm<sup>3</sup> of dichloromethane and washed with 10 cm<sup>3</sup> of de-ionized water three times to remove the un-reacted ArCOONa and TBPB. After purification to remove dichloromethane, a gel form of ArCOOQ was obtained and then identified.

To form the third-liquid phase, a large excess of inorganic salt (typically NaBr) was added into a mixture of 20 cm<sup>3</sup> of aqueous solution containing ArCOONa and TBPB and 20 cm<sup>3</sup> of toluene. The mixture was shaken at 70 °C for 15 min. A middle liquid layer (third-liquid phase) between aqueous and organic phase was formed. This third-liquid phase was separated to measure the volume and contents of ArCOOQ and QBr.

### 2.2. Analysis of ArCOOQ in the third-liquid phase

The amount of tetra-*n*-butylphosphonium cation (denoted as Q<sup>+</sup>) was determined by the titration method in a water–chloroform system using sodium tetraphenyl borate (Na<sup>+</sup>TBP<sup>-</sup>) as the titrant and bromophenol blue (0.2% in ethanol) as the indicator [8]. 10 cm<sup>3</sup>

of chloroform, 10 cm<sup>3</sup> of water and several drops of bromophenol blue were added into a flask containing the sample, and then the mixture was titrated with 0.05 N Na<sup>+</sup>TBP<sup>-</sup> solution. When the end point reached, the color of the chloroform layer changed from blue to colorless.

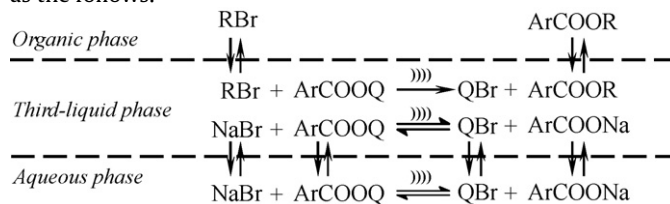
To determine the content of ArCOOQ in the third-liquid phase, a definite amount of methanol containing diphenylmethane (internal standard) was added into the third-liquid phase. A sample was withdrawn and diluted in 4 cm<sup>3</sup> of acetonitrile to analyze with HPLC (a C-18 (5-μm) type column and a variable-wavelength UV detector at 254 nm). The flow rate of the eluent (acetonitrile/methanol/water = 37/37/26 by volume) was 1.0 cm<sup>3</sup>/min.

### 2.3. Kinetic measurements of third-liquid phase catalyzed esterification

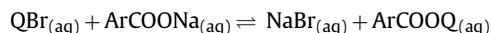
To perform the kinetic experiments, the third-liquid phase should first be prepared as described above. In a batch of run, the third-liquid phase, the aqueous and organic phases were mixed in a 250 cm<sup>3</sup> three-necked batch reactor, which was immersed in a constant-temperature water bath equipped with ultrasound irradiation. The organic reactant RBr together with a definite quantity of diphenylmethane (internal standard) was introduced to start the reaction under desired conditions. During the reaction, 0.2 cm<sup>3</sup> of the organic sample was withdrawn at the chosen time and analyzed by HPLC. After the reaction, the remaining third-liquid phase was measured and analyzed. For analyzing the third-liquid phase at each reaction time, the reaction had to be terminated at each selected time and the third-liquid phase was separated to analyze ArCOOQ and Q<sup>+</sup>.

## 3. Kinetic model

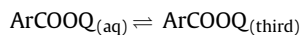
Under ultrasonic irradiation, the reaction scheme for the phase-transfer catalyzed esterification in the tri-liquid system is proposed as the follows.



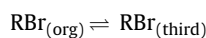
Considering the above scheme, the phase-transfer catalyst QBr first reacts with ArCOONa in the aqueous phase to produce ArCOOQ, and the rate of ionic reaction is usually very fast,



Then ArCOOQ transports from the aqueous phase into the third-liquid phase with a distribution constant  $K_{\text{ArCOOQ}}^{\text{aq}}$ , and RBr transfers from the organic phase into the third-liquid phase with distribution constant  $K_{\text{RBr}}^{\text{org}}$ ,



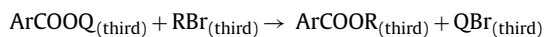
$$K_{\text{ArCOOQ}}^{\text{aq}} = \frac{C_{\text{ArCOOQ}}^{\text{third}}}{C_{\text{ArCOOQ}}^{\text{aq}}} \quad (1)$$



$$K_{\text{RBr}}^{\text{org}} = \frac{C_{\text{RBr}}^{\text{third}}}{C_{\text{RBr}}^{\text{org}}} \quad (2)$$

The intrinsic reaction is conducted by ArCOOQ with RBr within the third-liquid phase with the rate constant  $k$ , and the efficiency factor

of ultrasound irradiation on the intrinsic reaction is represented by  $\varepsilon$ ,



$$\frac{dC_{\text{ArCOOQ}}^{\text{third}}}{dt} = -\varepsilon k C_{\text{ArCOOQ}}^{\text{third}} C_{\text{RBr}}^{\text{third}} \quad (3)$$

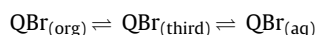
Substitution of Eq. (2) into (3) gives,

$$\frac{dC_{\text{ArCOOQ}}^{\text{third}}}{dt} = -\varepsilon k C_{\text{ArCOOQ}}^{\text{third}} K_{\text{RBr}}^{\text{org}} C_{\text{RBr}}^{\text{org}} \quad (4)$$

With a large excess of RBr, the term  $K_{\text{RBr}}^{\text{org}} C_{\text{RBr}}^{\text{org}}$  can be assumed constant, and the apparent rate constant  $k_{\text{app}}$  is expressed as  $k_{\text{app}} = \varepsilon k K_{\text{RBr}}^{\text{org}} C_{\text{RBr}}^{\text{org}}$ . Eq. (4) becomes

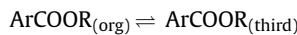
$$\frac{dC_{\text{ArCOOQ}}^{\text{third}}}{dt} = -k_{\text{app}} C_{\text{ArCOOQ}}^{\text{third}} \quad (5)$$

The produced QBr in the third-liquid phase then distributes into the organic and aqueous phases with equilibrium constants  $K_{\text{QBr}}^{\text{org}}$  and  $K_{\text{QBr}}^{\text{aq}}$ , respectively,



$$K_{\text{QBr}}^{\text{org}} = \frac{C_{\text{QBr}}^{\text{third}}}{C_{\text{QBr}}^{\text{org}}}, \quad K_{\text{QBr}}^{\text{aq}} = \frac{C_{\text{QBr}}^{\text{third}}}{C_{\text{QBr}}^{\text{aq}}} \quad (6)$$

The product ArCOOR transports from the third-liquid phase to the organic phase with the equilibrium constant  $K_{\text{ArCOOR}}^{\text{org}}$ ,



$$K_{\text{ArCOOR}}^{\text{org}} = \frac{C_{\text{ArCOOR}}^{\text{third}}}{C_{\text{ArCOOR}}^{\text{org}}} \quad (7)$$

Taking material balance for ArCOONa gives

$$\begin{aligned} V^{\text{aq}} C_{\text{ArCOONa},0}^{\text{aq}} &= V^{\text{aq}} (C_{\text{ArCOONa}}^{\text{aq}} + C_{\text{ArCOOQ}}^{\text{aq}}) \\ &+ V^{\text{third}} (C_{\text{ArCOOQ}}^{\text{third}} + C_{\text{ArCOOR}}^{\text{third}} + C_{\text{ArCOONa}}^{\text{third}}) \\ &+ V^{\text{org}} (C_{\text{ArCOOQ}}^{\text{org}} + C_{\text{ArCOOR}}^{\text{org}}) \end{aligned} \quad (8)$$

From experimental conditions, the amounts of ArCOONa in third-liquid phase and ArCOOQ in the organic phase are very small and can be ignored in the kinetic derivation. Eq. (8) is deduced as

$$\eta = \alpha_1 - \alpha_2 Y \quad (9)$$

where  $\eta = C_{\text{ArCOOQ}}^{\text{third}} / C_{\text{ArCOONa},0}$ ,  $Y = C_{\text{ArCOOR}}^{\text{org}} / C_{\text{ArCOONa},0}$ ,  $\alpha_1 = (V^{\text{aq}} / V_R) (1 - (C_{\text{ArCOONa}}^{\text{aq}} / C_{\text{ArCOONa},0}))$ ,  $\alpha_2 = V^{\text{org}} / V_R$  and  $V_R = V^{\text{aq}} / K_{\text{ArCOOQ}}^{\text{aq}} + V^{\text{org}} / K_{\text{ArCOOQ}}^{\text{org}} + V^{\text{third}}$ .

In Eq. (9), the term  $\alpha_1$  represents the initial amount of ArCOOQ in the third-liquid phase, and  $\alpha_2$  is the rate of consumption of ArCOOQ with respect to the product yield  $Y$ . These two parameters can be correlated from the plot of  $\eta$  versus  $Y$ . By substituting Eq. (9) into (5) and integrating the equation, a kinetic expression relating yield and time can be obtained,

$$-\ln(1 - \alpha_2 Y / \alpha_1) = k_{\text{app}} t \quad (10)$$

which is used to describe the kinetic behaviors of the reaction system.

## 4. Results and discussion

### 4.1. Formation of the third-liquid phase and the intrinsic reaction

In general, the third-liquid phase can be formed from the reaction of aqueous reactant, phase-transfer catalyst in the presence of extra salts in the aqueous phase and with low-polarity organic solvent. The third-liquid phase is a viscous layer between the aqueous and organic phases. The main constituent in the third-liquid phase is the catalytic intermediate. From the reaction of 0.0012 mol of ArCOONa and 0.001 mol of TBPB in 20 cm<sup>3</sup> of water at 70 °C, and after purification as described in Section 2.1, a viscous liquid ArCOOQ was obtained. The image of transmission electron microscopy (TEM) was taken to see the morphology of ArCOOQ, as shown in Fig. 1(a). It exhibits that ArCOOQ clusters were spherical in good dispersion and like a micelle. To see the intension of the third-liquid phase, with the conditions of 0.004 mol of ArCOONa, 0.003 mol of TBPB, 0.05 mol of NaBr, 20 cm<sup>3</sup> of water and 20 cm<sup>3</sup> of toluene, the third-liquid phase was formed. Fig. 1(b) is the TEM image of the separated third-liquid phase, showing the existence of inorganic salt, catalyst, catalytic intermediate and aqueous reactant residue.

The intrinsic reaction of ArCOOQ and RBr was performed to confirm the reaction mechanism of the phase-transfer catalyzed esterification in the third-liquid phase. 0.001 mol of prepared ArCOOQ and 0.001 mol of RBr were dissolved in 20 cm<sup>3</sup> of toluene to conduct the reaction at 70 °C under 28 kHz and 300 W of ultrasonic irradiation. Near 100% of the yield of product ArCOOR was achieved in 200 min of reaction, as shown in Fig. 2, demonstrating that the intrinsic reaction in the third-liquid phase is the key reaction step and is irreversible.

### 4.2. Effect of ultrasonic irradiation

In TLPTC, the catalytic intermediate ArCOOQ was produced from the ionic reaction of ArCOONa with QBr and then transferred into the third-liquid phase, the amount of ArCOOQ in the third-liquid phase would be gradually reduced with a large molar ratio of RBr to ArCOONa, due to the intrinsic reaction (Eq. (3)). Thus, a faster reaction rate would lead to a faster reduction of ArCOOQ. The ultrasonic irradiation can improve the transport of ArCOOQ between phases and provides local hot spots to enhance the reaction. Fig. 3 is the comparison of distribution of Q<sup>+</sup> in the aqueous, organic and third-liquid phases during the progress of reaction with and without ultrasonic irradiation. Initially, about 76% of catalyst stays in the third-liquid phase and 15% of catalyst exists in the aqueous phase. As the reaction proceeded, the decline of Q<sup>+</sup> in the third-liquid phase and slow increase of Q<sup>+</sup> in the aqueous phase shows the reactivity assisted by ultrasound at 28 kHz was much higher than that at silent condition.

The effect of different ultrasonic frequencies was performed at 28, 40, 50, and 80 Hz using 3 mmol of TBPB to produce the third-liquid phase. The product yield at silent condition was also compared, as shown in Fig. 4(a). The product yield in toluene phase in 100 min of reaction at silent condition was 32.1%; while with ultrasound irradiation at 28 kHz/300 W, the product yield in 100 min was raised to 97.4% and no other side products were detected. The near 100% of product yield indicated that the hydrolysis side-reaction of ArCOOR did not occur in this TLPTC system. The product yield decreased with increasing the ultrasonic frequency. The order of the reaction rate was 28 kHz > 40 kHz  $\approx$  50 kHz > 80 kHz  $\gg$  0 kHz. It is obviously that the overall reaction rate is highly promoted by the assistance of ultrasound. Fig. 4(b) shows the variation of ArCOOQ in the third-liquid phase for the four ultrasonic frequencies. The initial amount of ArCOOQ in the third-liquid phase was 2.19 mmol and decreased

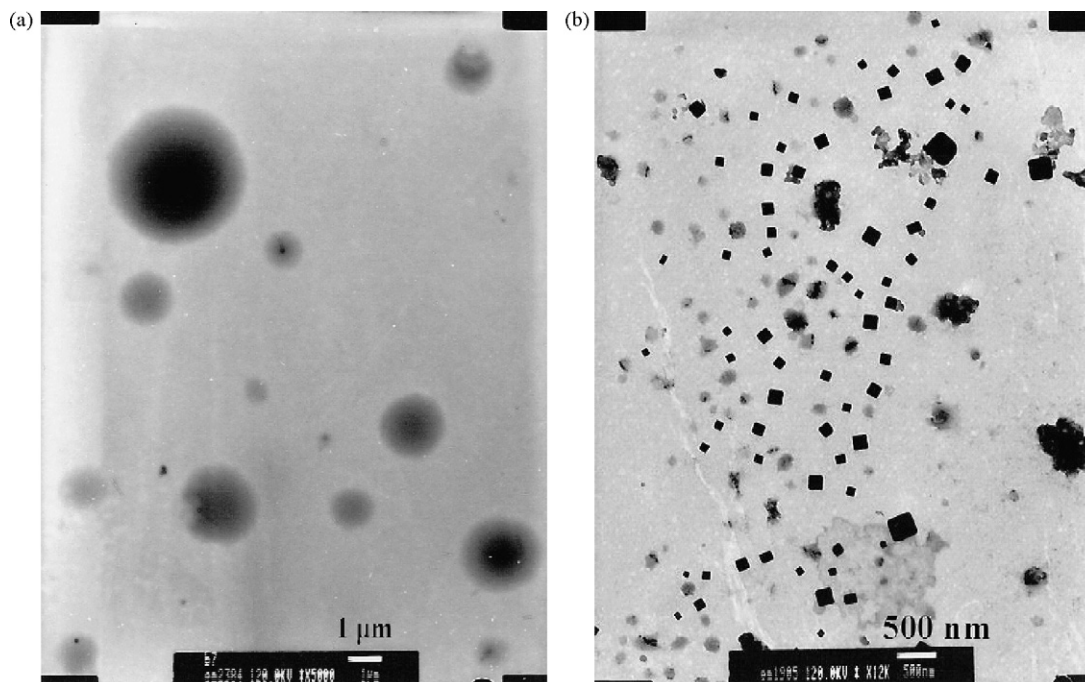


Fig. 1. TEM images: (a) tetrabutylphosphonium salicylate, (b) third-liquid phase formed by ArCOONa, TBPB, and NaBr at 70 °C.

with the progress of reaction. The reduction of ArCOOQ at 28 kHz was the fastest but differed not much with other frequencies. A fastest reduction in ArCOOQ implied a faster intrinsic reaction in the third-liquid phase. Only 0.14 mmol of ArCOOQ was retained in the third-liquid phase after 100 min of reaction. The variations of ArCOOQ were used to estimate reaction rates. By plotting  $\eta$  versus product yield  $Y$ , a linear relationship  $\eta = \alpha_1 - \alpha_2 Y$  would be obtained. The parameter  $\alpha_2$  indicates the consumption rate of ArCOOQ as a function of product yield. Since the variations of ArCOOQ for the frequencies at 28, 40, 50 and 80 kHz were small, an average value of 6.27 was correlated to represent  $\alpha_2$  for the four frequencies, as shown in Fig. 4(c). The value of  $\alpha_1$  was 7.31, exhibiting the initial effective activity of the catalyst. From this  $\alpha_1$  value, it shows the catalyst highly concentrated in the third-liquid phase to catalyze the reaction.

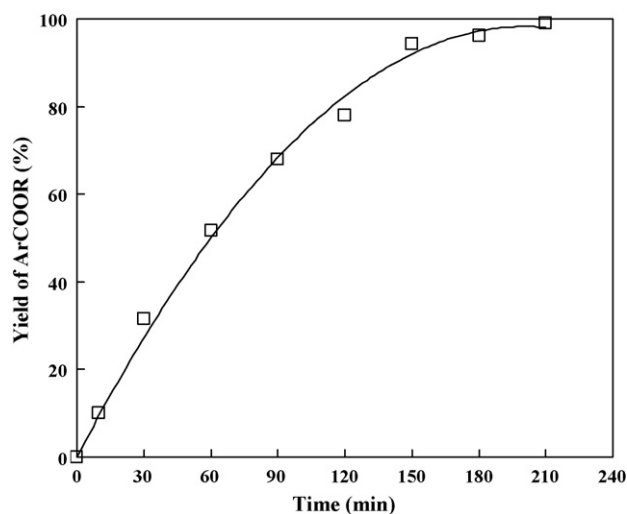


Fig. 2. Product yield of reaction of ArCOOQ and RBr vs. time; 1 mmol of ArCOOQ, 1 mmol of RBr, 20 cm<sup>3</sup> of toluene, 50 kHz and 300 W of ultrasound, 70 °C.

By applying  $\alpha_1$  and  $\alpha_2$  in Eq. (10), the apparent rate constants were correlated as 0.0201 min<sup>-1</sup> for 28 kHz, 0.0187 min<sup>-1</sup> for 40 kHz, 0.0173 min<sup>-1</sup> for 50 kHz, and 0.0149 min<sup>-1</sup> for 80 kHz, as shown in Fig. 4(d). The results demonstrate that the proposed kinetic equation can well describe the esterification catalyzed by ultrasound-assisted TLPTC. The results also indicate that a lower ultrasonic frequency enhances a higher reaction rate, and an optimal ultrasonic frequency might exist in a catalytic reaction [17,18]. The reason was possibly due to the cavitation phenomena. The cavitation occurring at a low frequency could be efficient to conduct the reaction inside the cavitating bubbles. At a high frequency the acoustic period was shorter with the decrease of the size of cavitating bubbles, leading to a higher cavitation threshold and decreasing the cavitation intensity [18]. Thus for this TLPTC system under ultrasound in the range of 28–80 kHz, the loss of power intensity at 80 kHz of ultrasonic waves was higher than that at 28 kHz, resulting in a lower reaction rate at 80 kHz. Fig. 5 shows the product yields

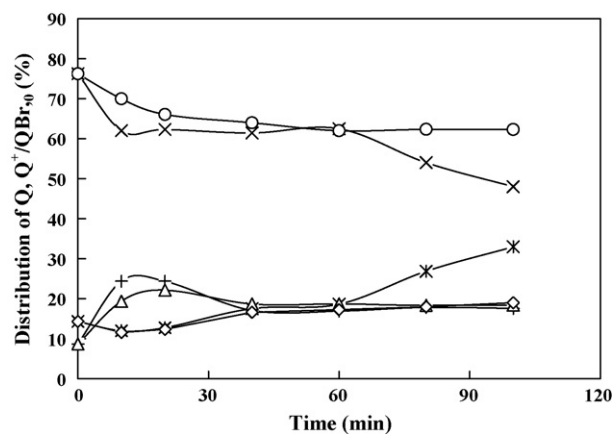
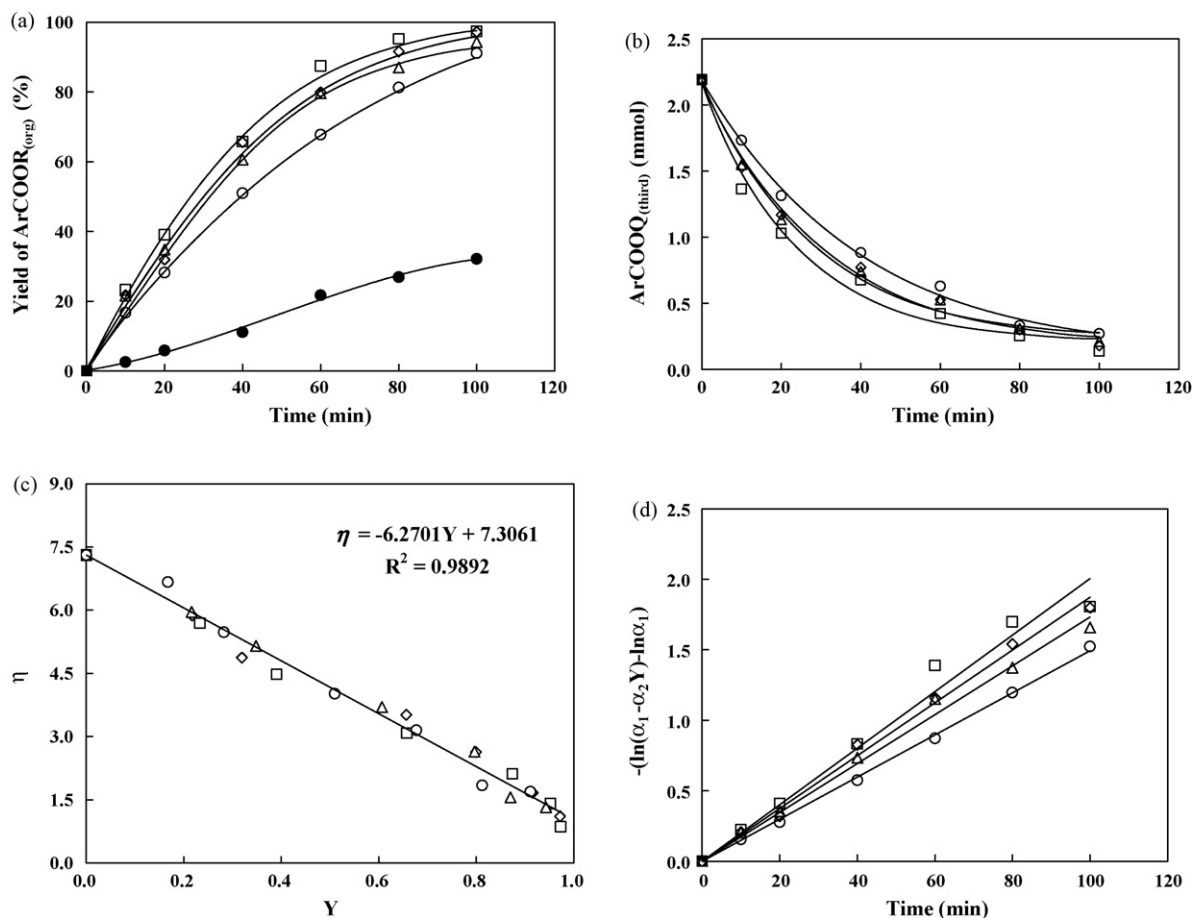


Fig. 3. Distribution of fraction of Q<sup>+</sup> between phases during the reaction. 4 mmol of ArCOONa, 48 mmol of RBr, 3 mmol of TBPB, 50 mmol of NaBr, 20 cm<sup>3</sup> of water, 20 cm<sup>3</sup> of toluene, 70 °C; for silence: (Δ) org., (◇) aq., (○) third-liquid; for 28 kHz/300 W: (+) org., (\*) aq., (×) third-liquid.

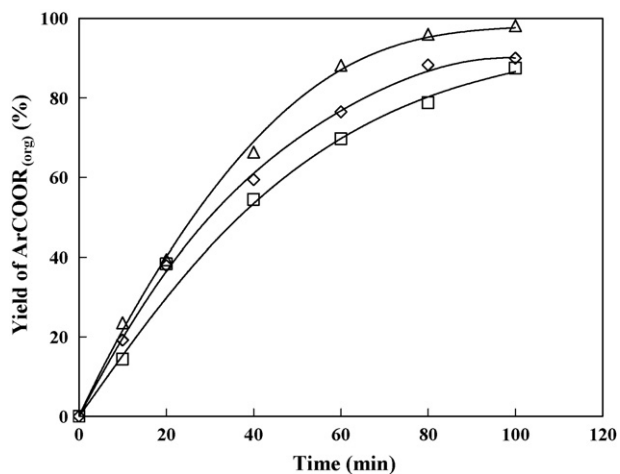


**Fig. 4.** Effect of ultrasound on (a) product yield in organic phase, (b)  $\text{ArCOOQ}_{(\text{third})}$ , (c)  $\eta$  vs. time, (d)  $-\ln(\alpha_1 - \alpha_2 Y) - \ln\alpha_1$  vs. time; 4 mmol of  $\text{ArCOONa}$ , 48 mmol of  $\text{RBr}$ , 3 mmol of  $\text{TBPB}$ , 50 mmol of  $\text{NaBr}$ ,  $20 \text{ cm}^3$  of water,  $20 \text{ cm}^3$  of toluene, 300 W of ultrasound,  $70^\circ \text{C}$ ; frequency of ultrasound: (●) 0 kHz; (□) 28 kHz; (◇) 40 kHz; (△) 50 kHz; (○) 80 kHz.

for different powers of ultrasound employed. As one expected, the reaction rate increased with the increase of ultrasound power supplied. This power effect is seen more significant for lower ultrasonic frequency.

#### 4.3. Effect of organic solvents and inorganic salts

Table 1 shows the effects of PTC, organic solvent and inorganic salts on the reaction under the condition of ultrasonic irradiation



**Fig. 5.** Effect of power of ultrasound on product yield in the organic phase; 4 mmol of  $\text{ArCOONa}$ , 48 mmol of  $\text{RBr}$ , 3 mmol of  $\text{TBPB}$ , 50 mol of  $\text{NaBr}$ ,  $20 \text{ cm}^3$  of water,  $20 \text{ cm}^3$  of toluene, 28 kHz of ultrasound,  $70^\circ \text{C}$ ; power of ultrasound: (□) 100 W; (◇) 200 W; (△) 300 W.

(50 kHz, 300 W). To form the third-liquid phase, a low-polarity solvent and extra inorganic salt should be used. Using tetra-*n*-butylammonium bromide (TBAB) and *n*-heptane, the generated volumes of third-liquid phase were  $1.8 \text{ cm}^3$  for  $\text{KBr}$ ,  $2.6 \text{ cm}^3$  for  $\text{NaBr}$ , and  $2.1 \text{ cm}^3$  for  $\text{NaCl}$ . The order of product yield after 180 min of reaction as well as the reaction rate for inorganic salts was  $\text{NaBr} > \text{KBr} > \text{NaCl}$ . Actually  $\text{Br}^-$  facilitates the anion-exchange reaction more than  $\text{Cl}^-$ . Comparing the effect of organic solvent, the reactivity in toluene was the highest to give the product yield of 89.1%, and the order of reaction rate was toluene > *n*-heptane/MIBK > isooctane  $\approx$  *n*-heptane. It means that the solvent with a higher polarity still enhanced the reaction rate much more than that with a lower polarity, even the low-polarity solvent was required in forming the third-liquid phase. Concerning the central atom of phase-transfer catalyst,  $\text{TBPB}$  (81.2% of product yield) shows a higher reactivity than  $\text{TBAB}$  (75.0% of product yield) with  $\text{NaBr}$  and *n*-heptane as the solvent. In addition, with 28 kHz and 300 W of ultrasonic irradiation on  $\text{TBPB}$  and toluene system for reactant ratio  $\text{RBr}/\text{ArCOONa}$  to be 10, the product yield increased to 92.0% after 100 min of reaction, also showing  $\text{TBPB}$  more active in this system.

#### 4.4. Effect of molar ratio of $\text{RBr}$ to $\text{ArCOONa}$

With the aqueous  $\text{ArCOONa}$  as the limiting reactant, the effect of  $\text{RBr}$  addition was performed with molar ratios of  $\text{RBr}$  to  $\text{ArCOONa}$  ( $r$ ) to be 2.5, 5, 10, 12, and 16 under 28 kHz and 300 W of ultrasound irradiation. As shown in Fig. 6, the product yield was strongly affected by the addition of  $\text{RBr}$  even with  $r \gg 1$ . The yield increased with the increase of  $r$  values up to  $r = 12$ , at which 96.7% of yield in

**Table 1**  
Effects of PTC, solvent and salts on the third-liquid catalyzed esterification.

PTC	Organic solvent	Inorganic salt	$V_{\text{third}}$ before reaction ( $\text{cm}^3$ )	$V_{\text{third}}$ after reaction ( $\text{cm}^3$ )	Product yield (%)
TBAB <sup>a</sup>	<i>n</i> -Heptane	KBr	1.8	1.2	65.5
	<i>n</i> -Heptane	NaBr	2.6	2.2	75.0
	<i>n</i> -Heptane	NaCl	2.1	1.8	56.3
	Isooctane	NaBr	2.8	2.0	74.6
	Toluene	NaBr	3.0	2.4	89.1
	<i>n</i> -Heptane/MIBK(3/7)	NaBr	2.8	2.0	84.1
TBPB <sup>a</sup>	<i>n</i> -Heptane	NaBr	2.5	1.6	81.2
TBPB <sup>b</sup>	Toluene	NaBr	1.0	0.5	92.0

<sup>a</sup> 2.5 mmol of ArCOONa, 25 mmol of RBr, 0.1 mol of inorganic salt, 20  $\text{cm}^3$  of organic solvent, 20  $\text{cm}^3$  of de-ionized water, 7 mmol of PTC, 50 kHz and 300 W of ultrasound irradiation, 80 °C, reaction time 180 min.

<sup>b</sup> 3.0 mmol of ArCOONa, 30 mmol of RBr, 0.1 mol of NaBr, 20  $\text{cm}^3$  of toluene, 20  $\text{cm}^3$  of de-ionized water, 2 mmol of TBPB, 28 kHz and 300 W of ultrasound irradiation, 80 °C, reaction time 100 min.

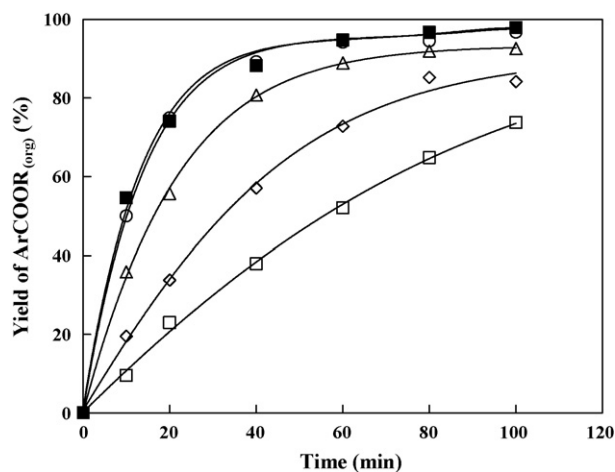
the organic phase can be attained after 100 min of reaction. This means that the amount of RBr transferring into the third-liquid phase would be greatly increased with a large excess of RBr. When the molar ratio of RBr to ArCOONa exceeded 12, the distribution of RBr into the third-liquid phase would reach a maximum. Thus, a favorable reactant ratio (RBr to ArCOONa) tends to be greater than 12.

#### 4.5. Comparison of stirring and ultrasound on the reaction rate

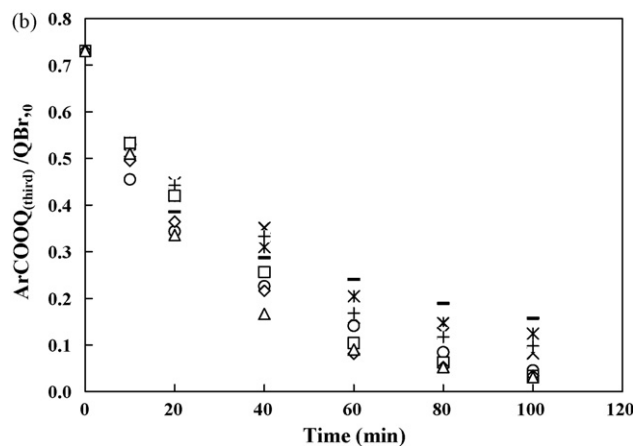
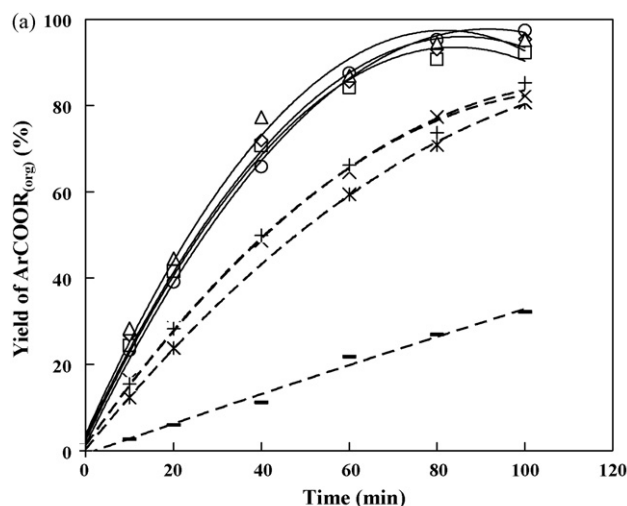
In multiphase reaction, an effective mixing is essential to promote the contact of immiscible reactants. For TLPTC, the main constituent in the third-liquid phase is the catalytic intermediate ArCOOQ which makes the third-liquid phase more hydrophobic, and the resistance of mass-transfer exists mainly in the third-liquid/aqueous interface more than in the organic/third-liquid side [8]. Increasing the stirring speed should reduce the mass-transfer resistance between phases. However, the effect of agitation on the reaction rate may change when the phase-transfer reaction is assisted by ultrasonic irradiation. As shown in Fig. 7(a), with or without 28 kHz/300 W of ultrasound for various stirring speeds were performed. Without stirring and at silent condition, 32.1% of product yield after 100 min of reaction can be obtained. This implies that the mass-transfer resistance of organic/third-liquid interface is small and RBr can transport into the third-liquid phase simply by molecular diffusion. At silent condition of TLPTC, the product yield after 100 min was 80.7% for 50 rpm, and about 85% for 100 or 200 rpm. The apparent reaction constants were corre-

lated as  $0.0147 \text{ min}^{-1}$  for 50 rpm,  $0.0158 \text{ min}^{-1}$  for 100 rpm, and  $0.016 \text{ min}^{-1}$  for 200 rpm. The overall reaction rate was affected by stirring only below 100 rpm.

Without agitation and under 28 kHz/300 W of ultrasonic irradiation, the product yield after 100 min was 97.4%; while for 50, 100, and 200 rpm, the product yields were 92.2%, 95.4% and 95.3%, respectively. The apparent rate constants were 0.0207, 0.0214, 0.0238, and  $0.0252 \text{ min}^{-1}$  for 0, 50, 100, and 200 rpm. For the testing stirring speeds, the reaction rates did not vary much under ultrasonic irradiation. The role of stirring on reducing the mass-transfer



**Fig. 6.** Effect of molar ratio of RBr to ArCOONa on product yield in the organic phase; conditions: 0.004 mol of ArCOONa, 0.003 mol of TBPB, 0.1 mol of NaBr, 20  $\text{cm}^3$  of water, 20  $\text{cm}^3$  of toluene, 28 kHz and 300 W of ultrasound, 80 °C; RBr/ArCOONa: (□) 2.5; (◇) 5; (△) 10; (○) 12; (■) 15.



**Fig. 7.** Effect of stirring on (a) the product yield (b)  $\text{ArCOOQ}_{(\text{third})}/\text{QBr}_0$ ; conditions: 0.004 mol of ArCOONa, 0.048 mol of RBr, 0.003 mol of TBPB, 0.05 mol of NaBr, 20  $\text{cm}^3$  of water, 20  $\text{cm}^3$  of toluene, 28 kHz and 300 W of ultrasound, 70 °C; stirring (rpm) for 28 kHz/300 W ultrasound: (○) 0; (□) 50; (◇) 100; (△) 200, for silent condition: (–) 0; (\*) 50; (×) 100; (+) 200.

resistance is not important. It is expected that ultrasound enhances the overall reaction rate by generating hot spots in the reaction zone, which is mainly the third-liquid phase, and also diminishing the resistance of mass-transfer during the propagation of ultrasonic waves. From the fraction of added QBr in the form of ArCOOQ in the third-liquid phase for the above conditions, the faster consumption of ArCOOQ in the third-liquid phase was observed for the faster reaction rate, as shown in Fig. 7(b). This further confirms that the controlling step of the TLPTC falls in the reaction of ArCOOQ and RBr in the third-liquid phase, and ultrasound can provide an efficient enhancement in the reaction rate.

## 5. Conclusions

The esterification of sodium salicylate with butyl bromide to produce salicylic acid *n*-butyl ester was investigated via ultrasound-assisted third-liquid phase-transfer catalysis. The third-liquid phase contains a high concentration of catalytic intermediate to increase the intrinsic reaction rate. Tetrabutylphosphonium bromide and tetrabutylammonium bromide can form the third-liquid phase in this study. The reaction rate increases with increasing the addition of butyl bromide up to a molar ratio of butyl bromide to sodium salicylate being 12. The production yield was 97.4% after 100 min of reaction with TBPB as the catalyst and under 28 kHz/300 W of ultrasound at 70 °C. Combining ultrasound and stirring promotes the reaction rate very much. Mass-transfer resistance can be neglected as the stirring speed exceeds 100 rpm. The apparent rate constant increases 53.3% when the reaction was enhanced by ultrasonic irradiation.

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