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ORIGINAL CONTRIBUTIONS

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Theoretical study on colloid/or inorganic material preparation by moving reaction boundary method in gel

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Abstract The method of moving reaction boundary (MRB) holds some significance for the colloid/or inorganic material synthesis, besides isoelectric focusing and capillary electrophoresis. However, theoretical studies have not been conducted for materials prepared by the moving reaction boundary method (MRBM). The concepts of product-concentration, product-rate and product-density of electro-migration reaction precipitate in MRBM were evolved. Some expressions were defined from the evolved concepts. The expressions were partially verified by some quantitative experiments of MRB with cobalt and hydroxyl ions in agarose gel. The theory developed here is of obvious significance for designing a new method preparing colloidal particles, for uniformly precipitating inorganic salts within gels, and for controlling the product-concentration, product-rate and product-density of electromigration reaction precipitate (viz. colloid/or inorganic material) in gels by MRBM.

Keywords Colloid · Material preparation · Electrolyte · Electrophoresis · Gel · Moving reaction boundary

Abbreviations CE: Capillary electrophoresis · CZE: Capillary zone electrophoresis · IEF: Isoelectric focusing · MRB: Moving reaction boundary · MRBM: Moving reaction boundary method · SRB: Stationary reaction boundary · SNRB: Stationary neutralization reaction boundary

Introduction

In 1970, Deman–Rigole [1, 2] first advanced the very important idea of “precipitate reaction front”, viz the pioneer concept of moving reaction boundary (MRB), and carried out the qualitative experiments of electromigration precipitate reaction in U-shaped tubes filled with the anti-convection medium of agar gel and observed the movement of ‘precipitate reaction front’. In 1993, Pospichol et al. [3] developed the concept of stationary neutralization reaction boundary (SNRB) formed by strong acid and base and created two SNRBs in a controlled electro-focusing apparatus of capillary electrophoresis (CE).

During 1997–99, the authors evolved the concept of MRB [4, 5], coupled with stationary reaction boundary SRB) [6] and critical expressions [7] for MRB and isoelectric focusing (IEF) on the basis of Svensson’s [8, 9] and Vesterberg’s work [10, 11] in the 1960s. At the same time, the authors [12–14] performed quantitative experiments and showed the validity of the theory for the MRB formed with cobalt and hydroxyl ions in agarose gel. The authors also performed experiments of MRB with strong hydrochloric acid and alkali sodium hydroxide and verified the validity of the theory for strong acid and alkali systems[15–17]. However, in the experiments of MRB formed with weak electrolytes [18–20], in-validity of the theory was found if there was a background electrolyte, such as potassium chloride, in large concentrations; and the corrected equations of MRB are directly formulated for those given experimental conditions [18–20].

Furthermore, the concept of MRB was used for the studies on electrophoresis. The theory of MRB was applied to the dynamic investigations on Svensson's classic IEF by Cao [21–23] and Pospichal et al. [24]. The MRBM was also used for the enhancement of separation efficiency of capillary zone electrophoresis (CZE) of amino acids like tryptophan and phenylalanine [25]. It was proved that even at high salt concentrations in the sample matrix, good improvement of separation efficiency of CZE was still obtained and over 200-fold online pre-concentration of analytes could be easily achieved by using the MRBM [26]. The theory on the pre-concentration of analytes by MRB in CZE was developed for a sensitive improvement of zwitterionic analyses and could be directly used for the accurate prediction on the experimental conditions of zwitterionic pre-concentration [27]. Recently, MRB-induced separation of zwitterions was observed [28] and higher than three millions fold enhancement of detective sensitivity of CE was easily achieved by the pre-concentration induced by MRB [29].

Significantly, we used MRBM for the preparation of stable colloidal particles in agarose gel [30]. Quantitative investigation was performed [31]. We consider, it is necessary to control product-concentration, product-rate, and product-density of a chemical reaction precipitate, such as colloidal $Co(OH)_2$ in gels, in a MRB system. However, up to now, these concepts of product-rate and product-density as well as product-concentration have not been evaluated.

Therefore, the main purposes in this study are to develop these concepts, such as product-concentration, product-rate and product-density of chemical reactive precipitate in a MRB system and to directly formulate the expressions for these concepts without detail derivations. The validity of the developed theory is partially proved by the quantitative experimental investigations [31].

Notations

c Equivalent concentration ($\mathrm{equiv/m^3}$).

The subscripts + and − indicate the positive and negative reaction ions, respectively, the subscript of "pro" means the 'concentration of electromigration reaction product', the superscripts α and β imply phase α and β, respectively, and the bar − over 'c' indicates the constituent concentration. Signed quantity, positive if the ion carries net positive charge(s), and negative if net negative charge(s), as has been set by numerous workers [4–7, 32–37].

m Mobility(m^2/s/V).

The subscripts + and − indicate the positive and negative reaction ions, respectively, and the superscripts α and β imply phase α and β, respectively, the bar − over 'm' implies the constituent mobility. Signed quantity like c.

κ Specific conductivity (S/m).

The superscript α and β imply phase α and β, respectively.

I Electric current (A).

q Cross-sectional area ($\mathrm{m^2}$).

R_{rate} Product equivalent number of electromigration reaciton precipitate in a MRB system in unit-time (equiv/s) [see the defining expression of Eq. 6].

R_{den} Product equivalent number of electromigration reaction precipitate in a MRB system in unit-time and unit-cross-area ($\mathrm{equiv/s/m^2}$) [see the defining expression of Eq. 9].

E Electric field strength (V/m)

$$E = \frac{I}{q\kappa}. \tag{1}$$

$\mu^{\alpha\beta}$ Velocity of boundary displacement (m/s). Signed quantity as shown in Fig. 1, positive if the boundary moves towards the cathode, negative if towards the anode, double superscripts indicate the two phases on either side of a boundary.

r_{R} Relative constituent mobility of constituent R (dimensionless) [5, 32–37].

$$\bar{r}_R = \frac{\bar{m}_R}{m_{\mathrm{Na^+}}}. \tag{2}$$

σ Relative conductance (C/m) [5, 32–37]

$$\sigma = \frac{\kappa}{m_{\mathrm{Na^+}}}. \tag{3}$$

Theory

Model

The model used here is given in Fig. 1. For ease of purpose, the following assumptions are made: (1) the ionic mobility is constant; (2) the boundary is at an idealized steady-state; (3) there are no bulk flows of solvent caused by Joule's heating and diffusion; (4) the product of the electromigration chemical reaction, such as colloidal material of $Co(OH)_2$ precipitated in a gel by MRBM is uniform. Thus, we can define the 'product-concentration', even the product is precipitated, e.g., $Co(OH)_2$ in Deman–Rigole's [1, 2] and the authors' [18,

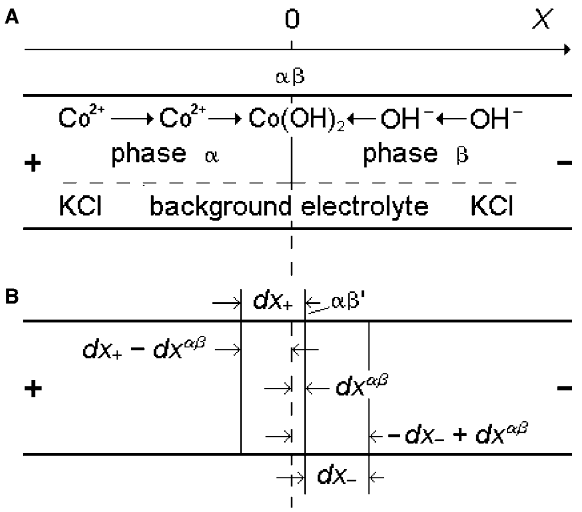

Fig. 1 The model of moving chemical reaction boundary formed with cobaltic and hydroxyl ions (with/or without background electrolyte potassium chloride). (**a**) shows the initial boundary, (**b**) shows the movements of the boundary and phase α and β, on the passage of electric current. The symbols of "+" and "−" mean the anodic and cathodic sides respectively, the symbols of $\mathrm{d}x_+$ and $\mathrm{d}x_-$ mean the displacement of cobalt and hydroxyl ions in $\mathrm{d}t$ time, $\mathrm{d}x^{\alpha\beta}$ the displacement of boundary αβ in $\mathrm{d}t$ time. The boundary velocity is given as $\mu^{\alpha\beta} = \mathrm{d}t^{\alpha\beta}/\mathrm{d}t$, the displacement of positive reactive cobalt ion is expressed as $\mathrm{d}x_+ = m_+\alpha\ E^\alpha\ \mathrm{d}t$, and that of negative reactive hydroxyl ion as $\mathrm{d}x_- = m_-{}^\beta\ E^\beta\ \mathrm{d}t$. For the other symbols see the text

19] experiments. These assumptions have been used by many researchers [2–7, 32–37] and have been partially proved by our data [38].

Theory for strong electrolyte system

If an electric field is used in Fig. 1, a chemical reaction may occur due to the positive and negative reactive ions such as cobalt and hydroxyl migrating in opposite direction. If a gel is used as a medium of anti-convection of solution, the precipitated cobalt hydroxide by the electromigration chemical reaction can exist in the gel in very fine grains [1, 2, 12–14]. Macroscopically, the reaction product may be uniformly distributed in the medium, if the experimental conditions are well controlled. Thus, we can advance the concept of "concentration of electro-migration reaction product", namely, c_{pro}, as will be given in Eq. 4. During the chemical reaction of electromigration, obviously, *the equivalent numbers of the positive and negative reaction ions that move from their phases into the MRB is always equal to each other*, as has been analyzed by Deman-Rigole [1, 2] and the authors [4, 5], namely, there exists

$$\begin{aligned} q(m_+^\alpha\ E^\alpha\ -\ \mu^{\alpha\beta})\,\bar{c}_+^\alpha\ &=\ (-\,m_-^\beta\ E^\beta +\ \mu^{\alpha\beta})(-\,c_-^\beta) \\ &= q\mu^{\alpha\beta}c_{\mathrm{pro}} \end{aligned} \tag{4}$$

where, the boundary velocity is given as [4, 5]

$$\mu^{\alpha\beta} = \frac{m_+^\alpha c_+^\alpha E^\alpha - m_-^\beta c_-^\beta E^\beta}{c_+^\alpha - c_-^\beta} \tag{5}$$

Product concentration

If the precipitate product yielded by MRB is uniformly distributed within gel as assumed in Sect. 3.1, we have the concept of a product- concentration. The concept is defined as a concentration of a chemical reactive precipitate that is produced by an electromigration reaction between positive and negative ions in an electric field. Its dimension is equiv/m^3. By inserting Eq. 5 into Eq. 4, one get the following expression of production-concentration,

$$c_{\mathrm{pro}} = c_+^\alpha c_-^\beta \frac{m_-^\beta E^\beta - m_+^\alpha E^\alpha}{m_+^\alpha c_+^\alpha E^\alpha - m_-^\beta c_-^\beta E^\beta}. \tag{6}$$

With the aid of Eq. 1, Eq. 6 may expressed as

$$c_{\mathrm{pro}} = c_+^\alpha c_-^\beta \frac{m_-^\beta \kappa^\alpha - m_+^\alpha \kappa^\beta}{m_+^\alpha c_+^\alpha \kappa^\beta - m_-^\beta c_-^\beta \kappa^\alpha}. \tag{7}$$

Being expressed with Eq. 2 and 3, then Eq. 7 may be changed as

$$c_{\mathrm{pro}} = c_+^\alpha c_-^\beta \frac{r_-^\beta \sigma^\alpha - r_+^\alpha \sigma^\beta}{r_+^\alpha c_+^\alpha \sigma^\beta - r_-^\beta c_-^\beta \sigma^\alpha}. \tag{8}$$

Product rate

From the ideal of product-concentration of precipitate, the concept of product rate can be developed. The product rate can be defined as equivalent number of product yielded by MRB in unit-time. Its dimension is equivl/s. The product rate can be mathematically given as

$$(\bar{m}_+^\alpha\ E^\alpha\ -\ \mu_{\mathrm{weak}}^{\alpha\beta})\,\bar{c}_+^\alpha\ =\ (-\,\bar{m}_-^\beta\ E^\beta +\ \mu_{\mathrm{weak}}^{\alpha\beta})(-\,\bar{c}_-^\beta). \tag{9}$$

Inserting Eq. 5 into Eq. 9, one obtains

$$R_{\mathrm{rate}} = q(m_-^\beta E^\beta - m_+^\alpha E^\alpha)\frac{c_+^\alpha c_-^\beta}{c_+^\alpha - c_-^\beta} \tag{10}$$

$$R_{\mathrm{rate}} = I\,\frac{m_-^\beta \kappa^\alpha - m_+^\alpha \kappa^\beta}{\kappa^\alpha \kappa^\beta}\frac{c_+^\alpha c_-^\beta}{c_+^\alpha - c_-^\beta} \tag{11}$$

The combination between Eqs. 2–3 with Eq. 11 yields

$$R_{\text{rate}} = I\frac{r_-^\beta\sigma^\alpha - r_+^\alpha\sigma^\beta}{\sigma^\alpha\sigma^\beta}\frac{c_+^\alpha c_-^\beta}{c_+^\alpha - c_-^\beta}. \tag{12}$$

Product density

The product equivalent number of electromigration reaction precipitate in a MRB in unit-area and unit-time is defined as the product-density. Its dimension is equiv/s^1/m^2 . Hence, Eq. 9 divided by the cross-area of tube q, one can achieve the following expression that defines the concept of product-density.

$$R_{\text{den}} = \left(m_+^\alpha E^\alpha - \mu^{\alpha\beta}\right)c_+^\alpha = -\left(m_-^\beta E^\beta + \mu^{\alpha\beta}\right)\left(-c_-^\beta\right) \tag{13}$$

Thus, with the aids of Eq. 5, one has

$$R_{\text{den}} = \left(m_-^\beta E^\beta - m_+^\alpha E^\alpha\right)\frac{c_+^\alpha c_-^\beta}{c_+^\alpha - c_-^\beta} \tag{14}$$

$$R_{\text{den}} = \frac{I}{q}\frac{m_-^\beta\kappa^\alpha - m_+^\alpha\kappa^\beta}{\kappa^\alpha\kappa^\beta}\frac{c_+^\alpha c_-^\beta}{c_+^\alpha - c_-^\beta} \tag{15}$$

$$R_{\text{den}} = \frac{I}{q}\frac{r_-^\beta\sigma^\alpha - r_+^\alpha\sigma^\beta}{\sigma^\alpha\sigma^\beta}\frac{c_+^\alpha c_-^\beta}{c_+^\alpha - c_-^\beta} \tag{16}$$

Deman-Rigole's product concentration

If uniform electric field exists over a conductor, viz,

$$E^\alpha = E^\beta \tag{17a}$$

$$\kappa^\alpha = \kappa^\beta \tag{17b}$$

is present, then Eqs. 6–8 become

$$c_{\text{pro}} = c_+^\alpha c_-^\beta\frac{m_-^\beta - m_+^\alpha}{m_+^\alpha c_+^\alpha - m_-^\beta c_-^\beta} \tag{18}$$

$$c_{\text{pro}} = c_+^\alpha c_-^\beta\frac{r_-^\beta - r_+^\alpha}{r_+^\alpha c_+^\alpha - r_-^\beta c_-^\beta} \tag{19}$$

Equation 18 was defined by Deman and Rigole [2] in 1970. Therefore, Deman–Rigole's expression of "concentration of electromigration reaction product" in a "precipitate reactive front" is a special case under which a uniform conductance is present. This is just the reason why Deman–Rigole's ideal of product concentration should be developed in the article.

Theory for weak electrolyte system

The expressions defined above are for a MRB created with a pair of strong positive and negative reaction electrolytes, rather than for a weak electrolyte system. Thus, for a weak electrolyte system, the above expressions should be defined with constituent concentration and mobility [5, 30], viz,

$$\bar{c} = \sum c_i \tag{20}$$

$$\bar{m} = \sum a_i\, m_I \tag{21}$$

where, a_I is the fraction of a subspecies of substance at equilibrium-state, viz,

$$a_i = \frac{m_i}{\sum m_i} \tag{22}$$

Therefore, with the aids of constituent concentration and mobility, we have the following several expressions for a weak electrolytic system.

Product concentration

The mathematical statements for the concentration of electromigration reaction product in a MRB formed in a weak electrolyte system are explicitly expressed as

$$c_{\text{pro}} = \bar{c}_+^\alpha\bar{c}_-^\beta\frac{\bar{m}_-^\beta E^\beta - \bar{m}_+^\alpha E^\alpha}{\bar{m}_+^\alpha\bar{c}_+^\alpha E^\alpha - \bar{m}_-^\beta\bar{c}_-^\beta E^\beta} \tag{23}$$

$$c_{\text{pro}} = \bar{c}_+^\alpha\bar{c}_-^\beta\frac{\bar{m}_-^\beta\kappa^\alpha - \bar{m}_+^\alpha\kappa^\beta}{\bar{m}_+^\alpha\bar{c}_+^\alpha\kappa^\beta - \bar{m}_-^\beta\bar{c}_-^\beta\kappa^\alpha} \tag{24}$$

$$c_{\text{pro}} = \bar{c}_+^\alpha\bar{c}_-^\beta\frac{\bar{r}_-^\beta\sigma^\alpha - \bar{r}_+^\alpha\sigma^\beta}{\bar{r}_+^\alpha\bar{c}_+^\alpha\sigma^\beta - \bar{r}_-^\beta\bar{c}_-^\beta\sigma^\alpha} \tag{25}$$

Product rate

The expressions for the rate of electromigration reaction product in a MRB for a weak electrolyte system are defined as

$$R_{\text{rate}} = q\left(\bar{m}_-^\beta E^\beta - \bar{m}_+^\alpha E^\alpha\right)\frac{\bar{c}_+^\alpha\bar{c}_-^\beta}{\bar{c}_+^\alpha - \bar{c}_-^\beta} \tag{26}$$

$$R_{\text{rate}} = I\frac{\bar{m}_-^\beta\kappa^\alpha - \bar{m}_+^\alpha\kappa^\beta}{\kappa^\alpha\kappa^\beta}\frac{\bar{c}_+^\alpha\bar{c}_-^\beta}{\bar{c}_+^\alpha - \bar{c}_-^\beta} \tag{27}$$

$$R_{\text{rate}} = I\frac{\bar{r}_-^\beta\sigma^\alpha - \bar{r}_+^\alpha\sigma^\beta}{\sigma^\alpha\sigma^\beta}\frac{\bar{c}_+^\alpha\bar{c}_-^\beta}{\bar{c}_+^\alpha - \bar{c}_-^\beta} \tag{28}$$

Product density

The expressions of product density in a MRB for a weak electrolyte system are expressly defined by the equations

$$R_{\mathrm{den}} = \left(\bar{m}_{-}^{\beta} E^{\beta} - \bar{m}_{+}^{\alpha} E^{\alpha}\right) \frac{\bar{c}_{+}^{\alpha} \bar{c}_{-}^{\beta}}{\bar{c}_{+}^{\alpha} - \bar{c}_{-}^{\beta}} \tag{29}$$

$$R_{\mathrm{den}} = \frac{I}{q} \frac{\bar{m}_{-}^{\beta} \kappa^{\alpha} - \bar{m}_{+}^{\alpha} \kappa^{\beta}}{\kappa^{\alpha} \kappa^{\beta}} \frac{\bar{c}_{+}^{\alpha} \bar{c}_{-}^{\beta}}{\bar{c}_{+}^{\alpha} - \bar{c}_{-}^{\beta}} \tag{30}$$

$$R_{\mathrm{den}} = \frac{I}{q} \frac{\bar{r}_{-}^{\beta} \sigma^{\alpha} - \bar{r}_{+}^{\alpha} \sigma^{\beta}}{\sigma^{\alpha} \sigma^{\beta}} \frac{\bar{c}_{+}^{\alpha} \bar{c}_{-}^{\beta}}{\bar{c}_{+}^{\alpha} - \bar{c}_{-}^{\beta}} \tag{31}$$

If a uniform electric field exists over a conductor, viz, Eq. 17 is present, then we derive from Eqs. 22–24

$$c_{\mathrm{pro}} = \bar{c}_{+}^{\alpha} \bar{c}_{-}^{\beta} \frac{\bar{m}_{-}^{\beta} - \bar{m}_{+}^{\alpha}}{\bar{m}_{+}^{\alpha} \bar{c}_{+}^{\alpha} - \bar{m}_{-}^{\beta} \bar{c}_{-}^{\beta}} \tag{32}$$

$$c_{\mathrm{pro}} = \bar{c}_{+}^{\alpha} \bar{c}_{-}^{\beta} \frac{\bar{r}_{-}^{\beta} - \bar{r}_{+}^{\alpha}}{\bar{r}_{+}^{\alpha} \bar{c}_{+}^{\alpha} - \bar{r}_{-}^{\beta} \bar{c}_{-}^{\beta}} \tag{33}$$

The expressions from Eq. 22 to Eq. 32 are all for a system of MRB created with weak positive and negative reactive electrolyte.

Experimental proofs

In Eqn. (18) or (19), if we set the concentration of positive reactive ions the same as that of negative reactive ions, viz, $c_{+}^{\alpha} = -c_{-}^{\beta}$, it is clear that we can get the equations

$$c_{\mathrm{pro}} = c_{+,-} \frac{m_{-}^{\beta} - m_{+}^{\alpha}}{m_{+}^{\alpha} + m_{-}^{\beta}} \tag{34}$$

$$c_{\mathrm{pro}} = c_{+,-} \frac{r_{-}^{\beta} - r_{+}^{\alpha}}{r_{+}^{\alpha} + r_{-}^{\beta}} \tag{35}$$

where, $c_{+,-}$ is the concentration of positive reactive ions or negative ones. Both Eqs. 34 and 35 indicate that the more concentrated the positive or negative reactive ions, the denser the product of electro-migration chemical reaction. This prediction is quantitatively manifested by the results of Fig. 4 in Reference [31].

In Fig. 4 of [31], the concentration of cobalt hydroxide in the gel is determined with an atomic absorption spectrophotometer equipped with a cobalt hollow cathode lamp operated at 1.3 mA. The determined concentration of cobalt hydroxide in the gel is quantitatively in agreement with the theoretical concentration predicted with Eq. 18 or Eq. 19: (1) correlative coefficient (CC) = 0.9983, (2) linear regression analyses between experimental and theoretical concentration of cobalt hydroxide (equiv/l) is $Y = -0.000754 + 1.07\,X$(Y = experimental value of cobalt hydroxide, X = theoretical value of cobalt hydroxide).

Discussion

We defined a series of expressions for the product concentration, the product-rate and product-density, for a strong electrolyte as well as a weak electrolyte system. These expressions such as Eqs. 5–18, show that, by choosing appropriate experimental conditions (e.g., the area of cross-section of the tube, the conductance of positive and negative reactive electrolytes, and the electric current/or field, etc.), one can control not only the velocity of the boundary movement, but also the product-concentration, the product-rate, as well as product-density of the electromigration reaction product. Some of those expressions were proved by the experiments of MRB with cobalt and hdyroxyl ions in Fig. 4 in reference [31]. Of course, it is necessary to perform further quantitative tests to validate the theory. The MRB is useful for designing a new preparative method of colloidal particles, and which has been proved in reference [22] and will be further discussed below.

The MRB can be used for preparing stable colloidal particles [30, 31], rather than unstable ones occurring in a direct chemical reaction between cobaltic and hydroxyl ions in solution or gel. It is well known that if cobalt hydroxide in solution it is immediately precipitated. Even in 1% agarose gel, the cobalt hydroxide formed large particles which could be easily observed with naked eyes (details not shown here). However, by using the MRBM, one observed a uniform yellow color of cobalt hydroxide (the color of oxidized cobalt ion, Co^{3+}) existing in the precipitation zone of cobalt hydroxide as displayed in Fig. 4 of reference [21]. This was also observed by Deman–Rigole [1, 2]. The colloidal particles of cobalt hydroxide are stable in the gel even at high background electrolyte KCl (up to 0.1 mol/l) [30]. More importantly, the concentration of the colloidal particles can be well controlled by changing the concentrations of positive and negative reaction electrolytes cobalt chloride and sodium hydroxide, and can be predicted with the "theory of product concentration" [see Eqs. 6–8, 18, 19, 23–25, 34–35] developed in this paper. The theoretical conclusions have been manifested by the experimental results in Fig. 4 in reference [31].

From the derivation above, it is evident that Eqs. 6–8, 18–19, 23–25 and 34–35 are the re-arrangments of original equations of MRB. These re-arrangements produce some new expressions of product concentration, product-rate and product-density dealing with Eqs. 6–8, 18–19, 23–25 and 34–35. Therefore, the original numerous experiments [12–24] that demonstrate the validity of equations of MRB also indicate the validity of Eqs. 6–8, 18–19, 23–25 and 34–35 developed from the concept of MRB. Of course, further systemic experimental investigations on the validity of these equations are necessary.

Furthermore, one can control the grain size of the colloidal particles. It was shown in Table 1 of reference [31] that the size of the colloidal particles decreases as the concentration of agarose gel increases from 1.0% to 1.5% and to 2.0%.

In conclusion, the paper developed some new concepts and equations on concentration, product-rate and product-density of "electromigration reaction products", such as colloidal $Co(OH)_2$ prepared by MRBM. Some of the equations have been verified by quantitative experiments of MRB with cobalt and hydroxyl ions in agarose gel, as well as by numerous experiments that originally show the validity of concept of MRB. The theory developed here possesses obvious significance for designing a new method of preparing colloidal particles, uniformly precipitating inorganic salts within gels, and for controlling concentration, product-rate and product-density of the electromigration reaction products in gels by MRBM.

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References

1. Deman J, Rigole W (1970) J Phys Chem 74:1122
2. Deman J (1970) Anal Chem 42:321
3. Pospichol J, Deml M, Bocek P (1993) J Chromatogr 638:179
4. Cao CX (1997) Acta Phys-Chim Sin 13:827
5. Cao CX (1998) Acta Chem Scand 52:709
6. Cao CX (1997) Acta Phys-Chim Sin 13:843
7. Cao CX, Zhu JH, Liu H, Fang WH, Tang WZ, Song LH, Chen WK (1999) Acta Chem Scand 53:955
8. Svensson H (1961) Acta Chem Scand 15:325
9. Svensson H (1962) Acta Chem Scand 16:456
10. Vestergerg O (1969) Acta Chem Scand 23:2653
11. Vesterberg O (1969) The synthesis of carrier ampholytes, USA Patent: 3,485,736
12. Cao CX, Chen WK (1998) Acta Chem Scand 52:714
13. Chen WK, Li RZ, Cao CX (1998) Acta Phys-Chim Sin 14:852
14. Chen WK, Bai JM, Li RZ, Cao CX (1998) Acta Phys-Chim Sin 14:913
15. Cao CX, Zhou SL, He YZ, Zheng XY, Chen WK, Qian YT (2000) J Chromatogr A 891:337
16. Zhou SL, Cao CX, He YZ, Chen WK, Qian YT (2000) Chinese Chem Let 12:179
17. Cao CX, Zhou SL, Qian YT, He YZ, Wang CR, Zheng XY, Chen WK (2002) J Chromatogr A 952:29
18. Cao CX, Zhou SL, He YZ, Qian YT, Yang L, Qu QS, Gan WE, Dong L, Zhao YQ, Chen WK (2001) J Chromatogr A 907:347
19. Cao CX, Zhou SL, Qian YT, He YZ, Yang L, Qu QS, Chen WK (2001) J Chromatogr A 922:283
20. Zhou SL, Cao CX, Qian YT, He YZ, Yang L, Qu QS, Chen WK (2002) Prog Nat Sci 12:667
21. Cao CX (1998) J Chromatogr A 813:153
22. Cao CX (1998) J Chromatogr A 813:172
23. Cao CX (1999) Prog Nat Sci 9:602
24. Pospichal J, Glovinova E (2001) J Chromatogr A 918:195
25. Cao CX, He YZ, Li M, Qian YT, Yang L, Qu QS, Zhou SL, Chen WK (2002) J Chromatogr A 952:39
26. Cao CX, He YZ, Li M, Qian YT, Gao MF, Ge LH, Zhou SL, Yang L, Qu QS (2002) Anal Chem 952:29
27. Cao CX, Zhang W, Qing WH, Li S, Liu W (2005) Anal Chem 77:955
28. Qin WH, Cao CX, Li S, Zhang W, Liu W (2005) Electrophoresis (in press)
29. Cao CX, Qing WH, Li S, Zhang W (2005) Anal Chem Electrophoresis (in press)
30. Cao CX, Li RZ, Zhou SL, Chen WK, Qian YT (2001) Colloid Surface A 180:17
31. Cao CX, Qian YT, Gan WE (2004) Colloid Polymer Sci 282:1059
32. Longsworth LG (1945) J Am Chem Soc 67:1109
33. Dole VP (1945) J Am Chem Soc 67:1119
34. Alberty RA (1950) J Am Chem Soc 72:2361
35. Nichol JC (1950) J Am Chem Soc 72:2367
36. Svensson H (1948) Acta Chem Scand 2:841
37. Hjelmeland LM, Chrambach A (1983) Electrophoresis 4:20
38. Li RZ, Xu HB, Cao CX (1999) Chem Online http://china.chemistrymag.org/col/1999/c99107.htm