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Minimum amount of extracting solvent of two-component extraction separation in a complex feeding pattern



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ABSTRACT

For a given countercurrent extraction separation, minimum amounts of extraction solvent and scrubbing agent solution indicating the limits of chemical consumptions are critical parameters for process design. The article derives the equations of those two minimum amounts for a two-component separation in a complex feeding pattern called “in-with-out” feeding by us. This feeding pattern leads out an organic stream from the stage that an aqueous feed enters or an aqueous stream from the stage that an organic feed enters. The exiting streams will serve as extracting solvent or scrubbing agent solution in other separation units, by which the overall chemical consumptions of an entire process can be decreased. Therefore the in-with-out feeding pattern is necessarily employed, especially in hyperlink extraction technology which has been widely applied to the rare earth separation industry in China with the aim of saving the use of chemicals. This work may significantly contribute to the theory of countercurrent extraction.

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1. Introduction

The minimum amount of extracting solvent (denoted hereafter as S_{\min}) and that of scrubbing agent solution (denoted hereafter as W_{\min}) indicate in theory the limits of chemical consumptions for a given countercurrent extraction separation, and therefore are important parameters of the processes [1,2]. The equations of both S_{\min} and W_{\min} for 2-component separations using either an aqueous feed or an organic feed have been given in the theory of countercurrent extraction which was primarily established by Prof. Xu in 1970s [1].

The theory of countercurrent extraction has contributed a lot to the development of rare earth separation processes in China [3–10]. In recent years, green chemistry processes have been paid much attention in extraction separation industry [11–17]. As mentioned in Refs. [12,16], hyperlink extraction technology was developed with the aim of saving both chemical consumptions and pollution emissions during extraction separation. The technology reduces the chemical consumptions mainly by supplying

rare-earth-contained extracting solvent or scrubbing agent solution mutually between two separation units, and therefore exerts its advantages in the separations of three or more components, such as the separations of rare earths. In the most practical cases, the amount of extracting solvent or scrubbing agent solution that one unit can supply does not exactly match its amount demanded by the other separation unit. To resolve this mismatch, the extra extracting solvent or scrubbing agent solution of a unit will be exported from the feeding stage of this unit, and used to another unit in order to avoid any extravagance. Thus a complex feeding pattern arises, that is, exporting an organic stream from the stage receiving an aqueous feed or an organic stream from the stage receiving an organic feed. We call this pattern as “in-with-out feeding”. This kind of feeding has been found to decrease total consumptions of acid and alkali during a hyperlink process of multi-component separation both in computational simulation and in industrial practices. However the theoretical equations of S_{\min} and W_{\min} in in-with-out feeding are not available yet. Due to the complicate mass balances in this feeding pattern, the present article is merely focused on the simplest case, i.e., A/B two-component separation, to deduce the equations of S_{\min} and W_{\min} . This work, together with our previous articles [18–20], is contributing to establish a new theory for the design of hyperlink extraction processes of multi-component separations.

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2. Description of the separation system

The derivation in this article will be performed on a countercurrent extraction separation of two components in in-with-out feeding pattern. A and B represent the components where A is more extractable than B, and their separation factor is β . The cascade couples n extraction stages and m scrubbing stages as shown in Fig. 1. The organic phase containing partly-saponified extracting solvent enters the cascade from 1st stage with a flowrate (hereafter in mole per unit time) of S , while hydrochloric acid flows into $(n + m)$ th stage of the cascade acting as scrubbing agent solution with a flowrate of W . The organic phase loading pure A and the aqueous phase containing pure B leave the cascade from stage $(n + m)$ and stage 1 respectively. A single aqueous or organic feed enters while an organic or aqueous stream is led out from stage n or stage $(n + 1)$ respectively, as displayed in Fig. 1. The aqueous feed flowrates of A and B are represented by $f_{A,a}$ and $f_{B,a}$ respectively and $f_{A,a} + f_{B,a} = f_a$, and meanwhile the exiting flowrates of A and B with the organic stream are denoted by y_A and y_B with $y_A + y_B = y_0$. Moreover in the case of organic feed used, the A and B flowrates with both the feed and the aqueous exiting stream are represented by $f_{A,o}$, $f_{B,o}$ and x_A , x_B respectively, where $f_{A,o} + f_{B,o} = f_o$ and $x_A + x_B = x_0$.

It is assumed that the extracting solvent and the aqueous solution are immiscible and remain so at all cases of the operation. It is assumed that each stage is an equilibrium stage, and therefore all the flowrates are out of each stage in equilibrium. It is also assumed that only the saponified extractant has the ability of extraction with a single cation-exchange mechanism. The saponified extracting solvent is supposed to be always saturated with components when leaving all stages except $(n + m)$ th stage. All the H^+ ion in the starting scrubbing acid is supposed to immediately exchange and migrate toward organic phase after entering the cascade, and therefore the scrubbing agent solution has contained no acid since leaving $(n + m)$ th stage. And also as the two components have the same valency, the mixed extraction factor, denoting the ratio of the total mole amount of the two components in the organic phase to that in the aqueous phase, will keep constant either through extraction stages except stage 1 or through scrubbing stages except stage $(n + m)$. Accordingly the flowrate of extracting solvent, represented by S , should be equal to the total organic flowrate of two components leaving all the extraction stages, and that of scrubbing agent solution, denoted by W , should correspond to the total aqueous flowrate leaving all the scrubbing stages.

3. Equations of S_{\min} and W_{\min} of a separation using an aqueous feed in in-with-out feeding pattern

Adjacent Stage Impurity Ratio (abbreviated as ASIR) [20] can quantitatively reflect the separation efficiency of a stage. ASIR dropping to 1 at a certain stage indicates that the extraction solvent or scrubbing agent solution has exhausted its separation

power due to disappearance of concentration driving force, and thus, no separation power for the feed is remained there. Accordingly S_{\min} and W_{\min} should correspond respectively to the flowrates of extracting solvent and scrubbing agent solution that are just enough to achieve the separation goal as well as to keep ASIR of at least one extraction stage and one scrubbing stage at 1. As discussed in our earlier works [18–20], ASIR always has the increase tendency from a central feed stage to two outlets, and therefore we shall derive the equations of S_{\min} and W_{\min} for a separation in in-with-out feeding based on the conditions that some continuous stages covering feed stage in the middle have the ASIR value of 1 and meanwhile the two pure components can be obtained in two opposite outlets.

In this article for simplicity, we only consider a 2-component separation in in-with-out feeding. We begin our discussion with the separation case using an aqueous feed. The stage receiving an aqueous feed is regarded as an extraction stage as specified in p. 627 of Ref. [1]. Fig. 2 displays the material flow information of 4 continuous stages including stage n (i.e. feed stage). In Fig. 2, $x_{i,k}$ and $y_{i,k}$ respectively represent the aqueous and organic flowrates of component i ($i = A$ or B) leaving stage k for left or right stage. As discussed above, if the separation cascade with enough stages is given both S_{\min} and W_{\min} , all of the 4 continuous stages should have the ASIR value of 1. In extraction section, component A is the impurity to be removed from the aqueous stream, and therefore for stage $(n - 1)$,

$$g_{n-1} = \frac{x_{A,n}}{x_{A,n-1}} = 1 \tag{1}$$

in which g_{n-1} represents ASIR of stage $(n - 1)$. According to the separation goal, the exiting aqueous phase from stage 1 should contain no component A, and also taking the mass balance of component A across interface I in Fig. 2, we can have:

$$x_{A,n} - y_{A,n-1} = x_{A,1} = 0 \tag{2}$$

From Eqs. (1) and (2), it can be known that

$$x_{A,n-1} = y_{A,n-1} \tag{3}$$

Therefore the relation of extraction equilibrium in stage $(n - 1)$ can be simplified as

$$\beta = \frac{y_{A,n-1} \cdot x_{B,n-1}}{x_{A,n-1} \cdot y_{B,n-1}} = \frac{x_{B,n-1}}{y_{B,n-1}} \tag{4}$$

Meanwhile considering that all the aqueous stream entering stage $(n - 1)$ will continue flowing to the left stage, one can be aware that

$$x_{A,n} + x_{B,n} = x_{A,n-1} + x_{B,n-1} \tag{5}$$

Thus

$$x_{B,n} = x_{B,n-1} \tag{6}$$

Then from the mass balance of component B across interface I in Fig. 2, we can acquire that

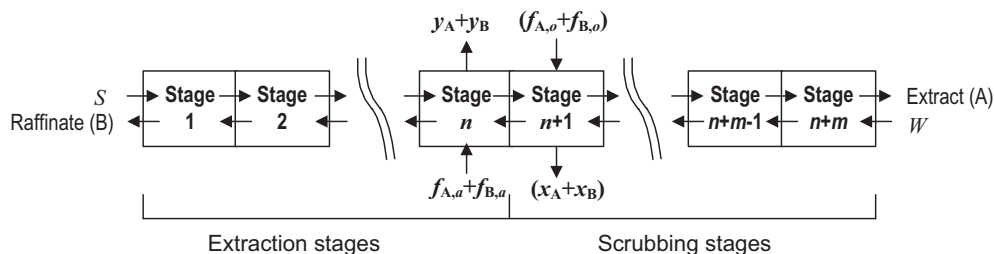


Fig. 1. A countercurrent multistage extraction cascade in in-with-out feeding pattern.

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