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Cost model for chitin production alkali wastewater recovery by couple-membrane filtration

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ABSTRACT

A model which can be applied to explore the impact of variables of couple-membrane system on the capital costs and operating costs is presented, in industrial filtration and sodium hydroxide recovery of the alkali wastewater from chitin production plants, for investment and operating costs of stainless steel ultrafiltration membrane (SSF) and alkali tolerant nanofiltration membrane (NF). The permeate flux models of SSF and NF set previously for these raw alkali wastewaters were used to simulate the filtration process. According to previously industrial experiments and actual investment data supplied by membrane manufacturers, the cost models were developed. Data used in simulations had been selected from previously pilot studies. For a normal design capacities (100 m^3/day), the trend of operating costs increases depends greatly on the module number of SSF. The total cost is the sum of capital costs and operating costs. Among the costs compositions, the capital costs of SSF is about 62% while that of NF is only 27%, and the operating costs is less than 11% of the total cost. The capital and operating costs decrease as the capacity of plants increase. The total cost decreases linearly with the increase of membrane permeates flux.

Keywords: Cost model; Chitin wastewater; Ultrafiltration; Nanofiltration; Alkali recovery

1. Introduction

The traditional production method of chitin is chemical way, while the huge sodium hydroxide consumption leads to the high production costs and severely environmental pollution issues, which greatly limits the development of chitin industry. Recovery of sodium hydroxide, water and protein from chitin alkali wastewater was investigated effectively using SSF ultrafiltration (UF) and nanofiltration (NF), which should be an effective solution to resolve pollution issues for chitin manufacturers [1]. It is convenient for manufacturers to directly evaluate the investment costs and operating costs according to the components of wastewater by some mathematic model tools.

Mathematic model is a mathematical tool which can be greatly reduced number of experiments and to guide the practice. The cost model is to give full consideration to a variety of common conditions of factories established on the basis of the capital costs and operating costs, and process the relationship between the relevant parameters. Cost models regarding to UF and NF are relatively rare, especially those on the alkali recovery from wastewater of chitin production by SSF and NF

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systems, no similar reports found. It is a requirement to develop and establish the cost models which are conducive to decision-making and to explore specific projects dealing with the relationship between design and operation. This work can be used to preliminary estimate of total treatment costs. The limit of the models is that they are only workable for the membrane and material used in this technology.

2. Modeling

In this study, assuming that the quality and composition of raw materials in same factory are relatively stable or less volatile; crab or shrimp shell was used as raw material, and the sodium hydroxide concentration is consistent, small fluctuations in composition of alkali wastewater; power, steam, staff salaries and other costs unchanged; all investment of equipments were at the current market price during the study and remained unchanged; non-membrane costs are associated with the membrane area. The experimental data of SSF and NF is quoted from the previous studies by L.M. Zhao et al. [1–3]. The cost of NF membrane is associated with the number of membrane tube. The models are applicable to industrial scale.

2.1. Modeling

Cost model can be disaggregated into capital cost (CC) and operating cost (OC). CC represents the investment required to provide a given capacity of NaOH solution production. CC includes the cost of land, engineering and technical skills, machinery and equipment, other necessary supporting wastewater treatment [4]. Investment was required to be calculated by basing on unit volume of production capacity in order to approximately estimate the annual capital cost.

OC included energy costs, chemicals for membrane cleaning, membrane replacement, process cost for concentration. Maximizing profits (or minimizing investment risks), and the allocation of resources within the enterprise, decision-making process must be based on the analysis of CC and OC over the lifetime of a project.

Since each complete system is facilities in need, and therefore the scope of this model includes the design is still incomplete. This work involved in the membrane components are of stainless steel tubular roll-type inorganic UF membrane and organic spiral-wound NF membranes, these two films are based on cross-flow filtration, so the material flow in the membrane is a tangent to the flow membrane surface, the transmembrane pressure provides the driven force.

The foundation of establishing the cost model is that the investment costs and operating costs are associated with the membrane area, while the membrane area is directly related with the flux. Therefore, the membrane flux models of membranes are demanded for accessing to area association model, which related with the capital costs and operating costs.

2.1.1. Capital cost

The CC comprises the non-membrane costs C_p and membrane components costs C_m, non-membrane costs includes all costs of equipment and facilities necessary, including pumps, valves, piping, automatic control systems, surveillance equipment. Required membrane area is the function of designed overall processing flow which is also a function of membrane flux. With the flux values during membrane filtration process constantly changing, J_v is commonly used to calculate the value of the average flux J_m. Modeling developed in this paper, assumed that for the specified operating conditions, the membrane flux is constant, that is, the J_m can be applied. Membrane area required can be calculated by the following formula:

$$A_{mem} = \frac{Q_{des}}{J_m t_o} \tag{1}$$

where, A_{mem} is membrane area, m^2; Q_{des} is total treatment capacity, m^3; J_m is average flux, LMH; t_o is filtration time, hr.

For the NF membrane, the membrane area of each membrane unit is 25m^2 as the manufacturers supported, and the membrane area demanded can be calculated from Eq. (1), and then the numbers of membrane module can be converted by Eq.(2) [5]:

$$n_{mod} = NEAREST\ INTEGER\left(\frac{A_{mem}}{A_{mod}} + 0.5\right) \tag{2}$$

where, A_{mod} is membrane area of each membrane component, n_{mod} is number of membrane module required. At least A_{mem}/A_{mod} modules must be used to meet the minimum requirement for membrane area and thus, it is necessary to round the number of modules to the next highest integer. In this article, single-tube membrane area of SSF is 0.693 m^2 with length of 6 m.

According to previous statements and assumptions, C_p is function of membrane area. This article assumes that the C_p general formula [6] as follows:

$$C_p = k \times (A_{mem})^n \tag{3}$$

where k is a constant representing the relative weight of a cost component; n is an exponent representing the economy of scale associated with a cost component.

Pump is critical engineering equipment with a key role in industry flow treatment, which contributes to mainly operation cost. For the pump costs, the relevant design parameter is the product of the pump flow and pressure, instead of the membrane area, while the flow and head depend on membrane area, so the CC of pump is still function of membrane area.

The data was collected from lots of practical engineering projects. The data was then calculated and treated, and simulated each of the individual C_p and the corresponding membrane area or number of membrane module, therefore all kinds of constants and factors in the C_p model formulas of SSF and NF were obtained by least square method. The estimate of capital cost is in accordance with the engineering data from Hydrochem Engineering (Shanghai) Co., Ltd., while a large number of actual data was also collected from the manufacturers of membrane components.

Generally *n* value is less than 1, it means that economies of scale increases when the treatment capacity increase, which according to economic laws, the larger the scale, the more obvious the scale of investment. *k* value representing the relative weight of equipment cost in a period of time when the price is relative stable, such as a work-years, and its value can be regarded as a constant. *n* value is the scale index, usually its value within the range of 0.4 ~ 0.75 [7].

C_p of SSF was calculated as follows:

$$C_{p\text{-}SSM} = 33261(A_{mem})^{0.55}\ (R^2 = 0.987) \tag{4}$$

C_p of NF system is:

$$C_{p\text{-}NF} = 5295.9(A_{mem})^{0.67}(R^2 = 0.99) \tag{5}$$

Membrane cost was proportional to area, quantity and price, and it was defined as the cost at purchase:

$$C_m = c_m \cdot A_{mem} \tag{6}$$

$$C_m = c_m \cdot n_{\text{mod}} \tag{7}$$

where c_m was the membrane price and C_m was membrane cost.

2.1.2. Cost of capital

Cost of capital, namely total capital costs, is defined as the cost of capital per unit alkali wastewater. C_p and C_m add up to the total investment cost, then depreciated according to the design life, and the annual investment cost was obtained. Annual investment cost divided by design capacity is the capital cost per unit alkali wastewater [5].

$$C_c = \frac{(C_P + C_m) \cdot (\frac{A}{P})}{Q_{desn}} \tag{8}$$

where C_c is Capital cost, CNY/L; Q_{desn} is Capacity of design, m^3; and *(A/P)* is Coefficient of amortization.

$$\frac{A}{P} = \frac{i_c \cdot (1 + i_c) \cdot DL}{(1 + i_c) \cdot DL - 1} \tag{9}$$

where *DL* is Design life, year; and i_c is discount rate.

Eq. (8) must be multiplied by a suitable constant to convert the time unit in the amortization factor and design capacity. Since Q_{desn} may lower than the actual capacity which is excess capacity, so when Eq. (8) provides excess capacity in the context of the total capital cost, the maximum capacity is substituted by Q_{desn} value.

2.1.3. Operating costs

Membrane system operating costs items include energy, membrane replacement, chemical (cleaning agents), labor, and concentration treatment.

Energy costs are calculated from the power requirements which are for pumping feed wastewater, recycling concentration, and membrane cleaning. The total energy costs obtained through which the sum of those three energy consumptions per unit volume of wastewater produced is multiplied by the price of power, then this model assumes that all of the membrane systems use single-stage recycling concentration, by this way, the liquid continues recycling and concentrating, only the permeate leaves system. During the concentration processing, power is needed for compensating the headloss across the module to maintain a mean cross-flow velocity through the membrane channels. The calculation method is different from one-stage method with multi-stage filtration which circulating pump also increases pressure for next stage membrane, so the energy consumption E_1 and E_2 of feed pumps and recycle pumps, as well as energy costs of cleaning E_3 can be calculated by literature methods [5,6,8], the total energy costs can be calculated by the price of power multiplied by the total energy consumption:

$$C_e = c_{kw} \cdot (E_1 + E_2 + E_3) \tag{10}$$

where C_e is the cost of energy per unit volume of wastewater, CNY/m^3; and c_{kw} is the price of electricity, CNY/J.

Generally, the SSF membrane can be replaced in a longer time which replacement cost was ignored here, and only the replacement cost of NF membrane was considered here. The membrane replacement cycle is function of the quality of feed; the cleaner the feed is, the longer period the membrane can be operated. This study assumed that the life of NF membranes is constant, and they were replaced at fixed intervals in factories. Then the membrane replacement costs during the whole plant design life can be estimated by Eq.(11) and Eq.(12) [5,9], by using the membrane life that the manufacturers supplied as the replacement cycle:

$$C_{mr} = \frac{(\frac{A}{F})\cdot c_{mod}\cdot n_{mod}}{Q_{desn}} \tag{11}$$

$$\frac{A}{F} = \frac{i_f}{(i_f+1)\cdot ML - 1} \tag{12}$$

where C_{mr} is membrane replacement cost, i_f is the annual discount rate for membrane replacement, expressed as a decimal fraction, *ML* is the membrane life, years.

The cleaning agents usually use 1% to 2% sodium hydroxide solution and 0.5% nitric acid. As the feed in this study is high concentration of caustic wastewater, NF membrane cleaning costs comparing to total operating cost can be ignored. The consumption of NaOH and HNO_3 is not too much in SSF cleaning. The chemicals using in the cleaning process are shown in Table 1:

Cleaning solution volumes, that of 60 m^2 SSF membrane is 3000 L/set, while that of 25 m^2 NF membrane is 50 L/set, hence, the total amount of cleaning agents can be calculated from Eq.(13), in which there contains 2 times of alkali wash while 1 time of acid wash after each batch of process:

$$C_{chem} = \frac{\sum_{i=1}^{n} c_{chem,i}\cdot d_{chem,i}}{t\cdot Q_{clean}} = \frac{Q_{clean}\cdot(2c_{NaOH}+0.063c_{acid})}{100t\cdot Q_{clean}} \tag{13}$$

where d_{chem} is dosage of each chemicals, m^3; Q_{clean} is the cleaning water amount, m^3; c_{chem} is price of each chemicals, CNY/t; and *t* is the processing time of each work cycle required, hr.

Table 1
Cleaning agents' costs

Chemicals	Amount % (wt/wt)	Price CNY/t	Type
NaOH	2	3250	98%
HNO_3	0.063(0.01 mol/l)	6000	99.50%

Note: Price data from China Chemical Network http://cn.chemnet.com/, March 2009.

2.2. Parameters for model calculations

The parameters for model calculations was listed in Table 2, which were supplied by manufacturers and pilot experiments.

3. Results and discussions

3.1. The effects of non-alkali solid concentration on costs

The trends of three kinds of costs followed the change of content of non-alkali solid concentration (NASC) are shown in Fig. 1. It shows in Fig. 1a that the CC increased with the increasing of NASC. And the amplitude of growth rate increased coupling with the increase of number of SSF modules, and the maximum value was about 0.38 CNY/L. Fig. 1b illustrates the relationship between OC and NASC,

Table 2
Parameters for model calculations

Parameter	SSF	NF
Facility life (year)	20	20
WMCO (Da)	––	150
Average membrane pore diameter (nm)	20	––
*Membrane cost (¥/m^2)	12000	625
Module length (m)	6	1
*Membrane life (year)	20	5
Module diameter (mm)	18.3	1.52
Feed pressure (bar)	3	30
Recovery (%)	90	95
Cross-flow velocity (m/s)	4~5	2.7
Cleaning frequency (times/day)	1	1
Cleaning time (hr)	2	1
Maximum pressure of feed pump (bar)	3	7
Maximum pressure of recycle pump (bar)	5	27
Headloss cross module(bar)	1.75 (60 m^2)	2 (4 modules)
Operation pressure (bar)	3.1	31
Clean processing pressure (bar)	2	5
Mean flux ($L\cdot m^{-2}\cdot h^{-1}$)	110	25
Cost of capital (interest, %)	7.83	7.83
Discount rate (%)	3.24	3.24
Efficiency of pump (%)	80	70
Temperature (C)	70~80	50
Design flow (m^3/hr)	15	15
*1 Design treatment amount per day (m^3)	100	100
*2 Price of power (CNY/Kw · h)	0.35	0.35

*1 based on the annual output of chitin of 1,000 tons.
*2 based on current costs from power plant (2009).
Notes: All prices based on market values at December 2009 level, and the prices of membranes was supplied by the membrane manufacturers; all the relevant parameters derived from membrane manufacturers or provided information by vendors.

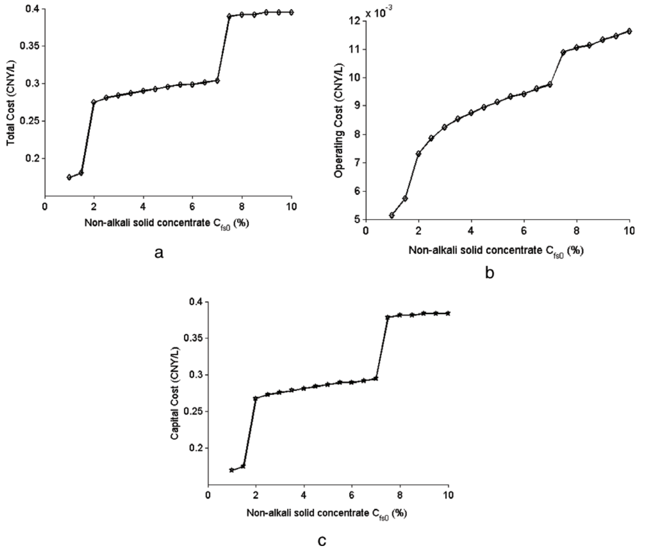


Fig. 1. Cost vs. NASC, (a) total cost; (b) operating cost; (c) capital cost.

it was easy to understand that the OC increased with the increase of NASC, and the maximum value of operating cost was 0.012 CNY/L. Hence, the equipments' investment costs are the mainly part in total costs. As shown in Fig. 1c, the total costs increased with the increase of NASC with a maximum value of 0.4 CNY/L.

Fig. 2a and Fig. 2b show that the maximum cost of SSF is about 0.28 CNY / L, which is about 56% of the total costs. Shown in Fig. 2c and Fig. 2d, the maximum cost of NF is about 0.11 CNY/L, which is more than 26% of the total costs.

3.2. The effects of membrane life on capital costs

Membrane modules were the essential component of the system, and also were the main parts of investment. The membrane elements (especially for organic polymer material membrane) would be damaged completely even once operation or preservation mistake. SSF membrane can be avoided from these kinds of damage since the consistency of stainless steel. Assumed the life of NF membrane ranged from 0.5 y to 5 y in this study. Fig. 3a and Fig. 3b show that the replacement cost of NF membrane and the CC increased with the decrease of the membrane life, while the extent of increase was also increased. It illustrated that the costs increased significantly at half a year membrane life.

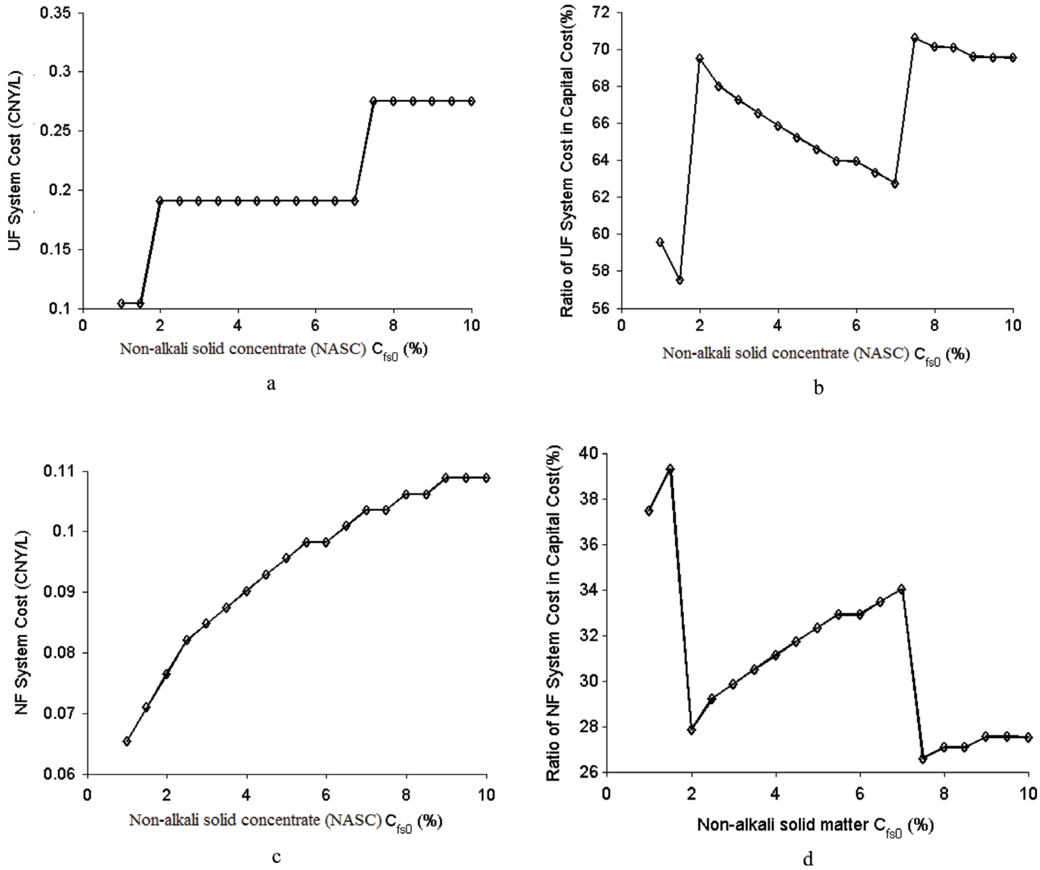
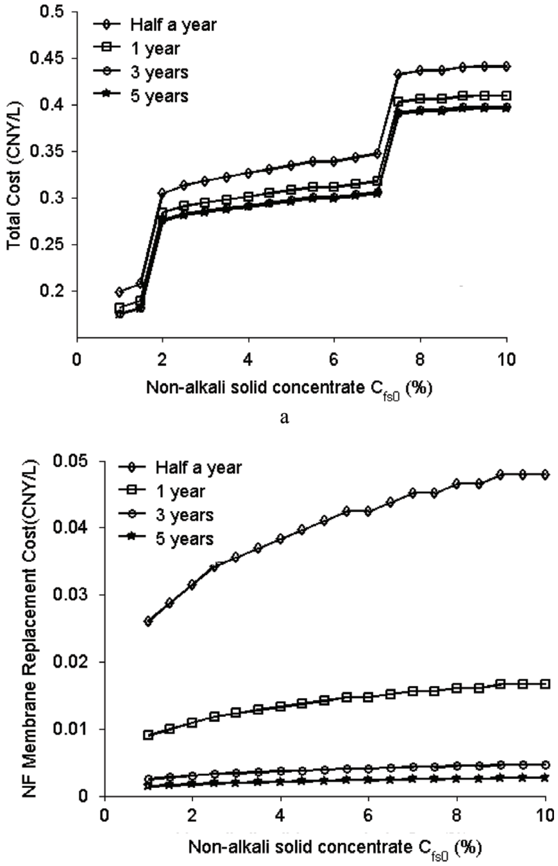


Fig. 2. (a) SSF equipment cost; (b) ratio of SSF equipment cost in total capital costs; (c) NF equipment cost; (d) ratio of NF equipment cost in total capital costs.



a

b

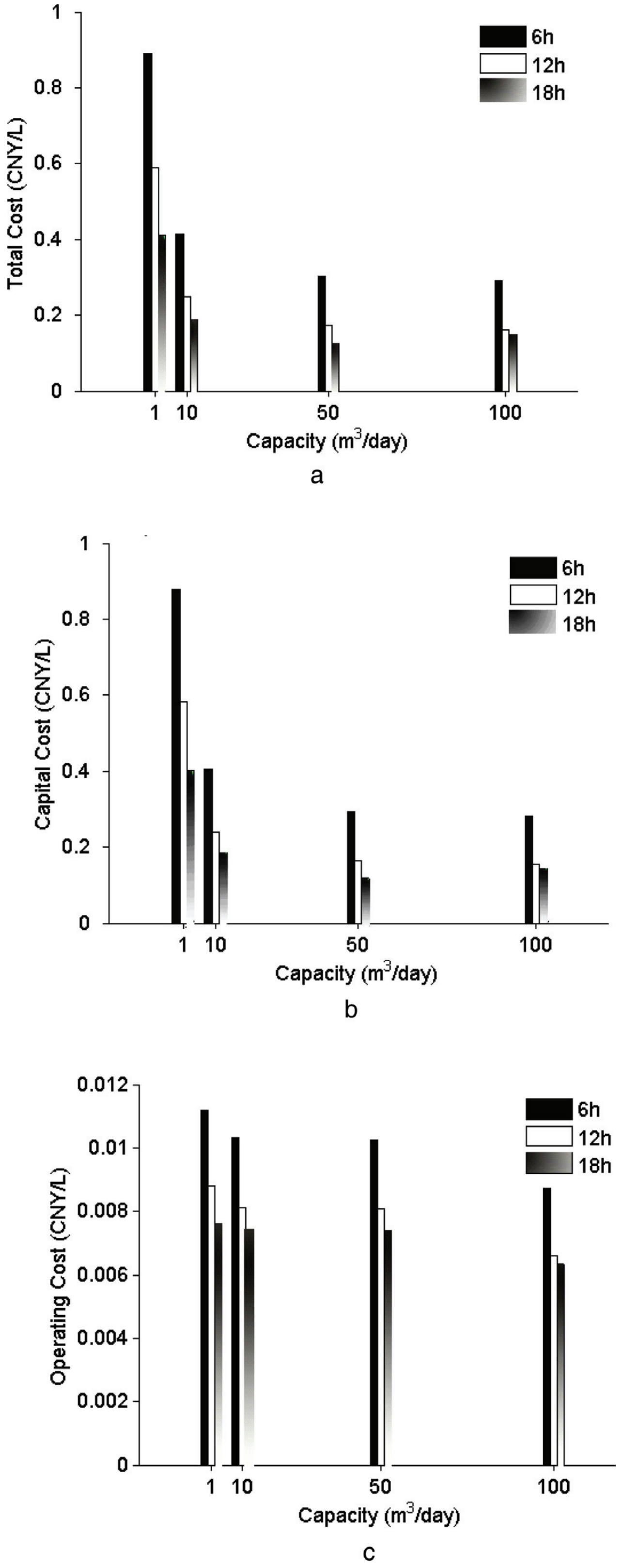
Fig. 3. The effects of NASC on total costs vs. NF membrane life; (a) Total costs, (b) Replacement cost of NF.

3.3. The effects of operating time on costs

As shown in Fig. 4, total costs, CC and OC decreased as the increment of operating time at the fixed design capacity. The longer the operating time, the less the membrane area need, which significantly decreased the CC. Although the increase of operating time will lead to the increment of energy cost, the extent of energy costs decrease due to the decrement of equipment amount was much more than the increase of energy cost due to the increase of operation time. The general result was the total costs decreased.

3.4. The effects of design capacity on the costs

As shown in Fig. 5, with the increment of design capacity, OC, CC and total cost decreased at the operating time 18 h. Since the membrane was provided by of integer, utilization efficiency of membrane was increased as the increment of treatment capacity, for instance, the costs at the capacity of 1 m^3/d were more expensive than that at all the others capacity and the costs can be decreased by using small area module.

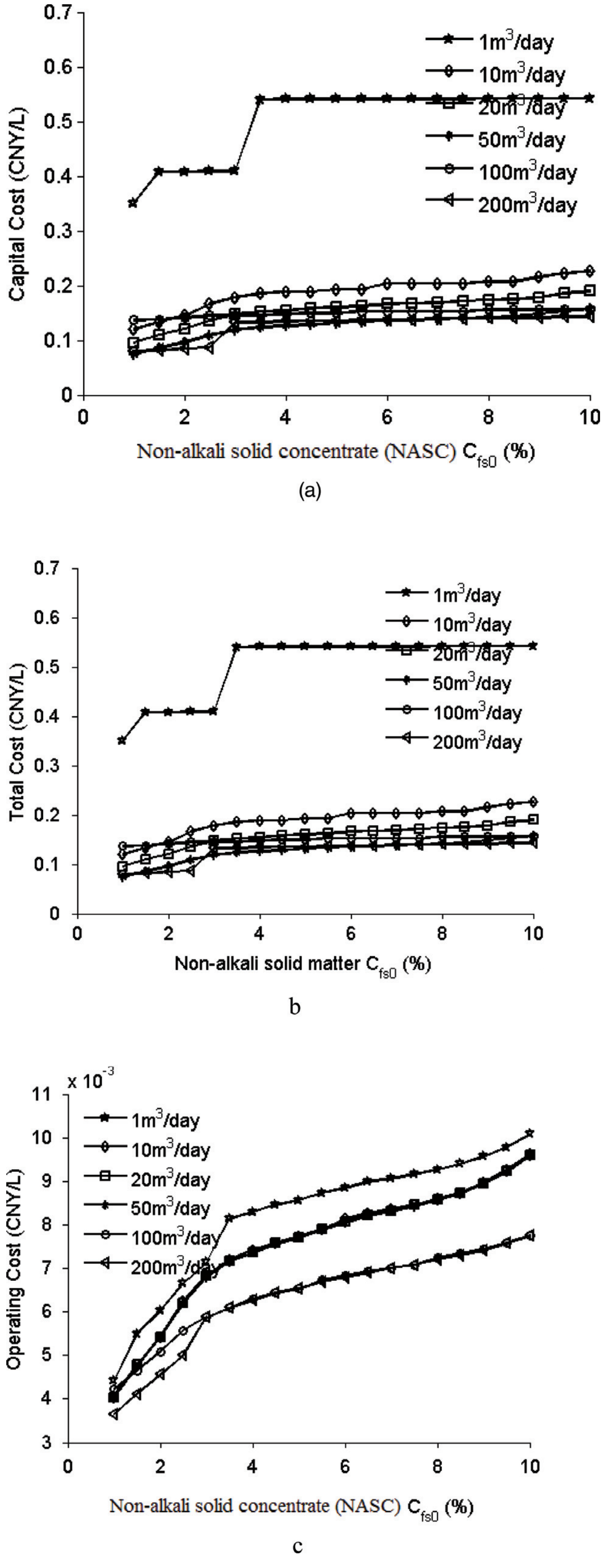


a

b

c

Fig. 4. Cost vs. treatment capacity and operating time under 4% NASC; (a) total costs, (b) capital costs, (c) operating costs.



(a)

b

c

Fig. 5. Cost vs. capacity and NASC under operating time 18 h; (a) capital cost, (b) total cost, (c) operating cost.

3.5. Flux on total investment costs

As shown in Fig. 6 and Fig. 7, SSF and NF investment increased with the increment of flux decline at the design treatment capacity of 100 m^3/d and 6 h per day of production time. Since the capacity of a single SSF module was higher than the capacity of a single NF module, the investment of SSF membrane area had more waste than the investment of NF (the steps in Fig. 6).

3.6. Model validation

According to the economic model in this study, the model simulation values were calculated. As shown in Fig. 8, unit volumes of the model simulation total cost of the treatment were similar to actual values, and the errors were of decrement as the increment of capacity. The correlation coefficient between a dozen of actual values and model values was 0.9984. All the other errors

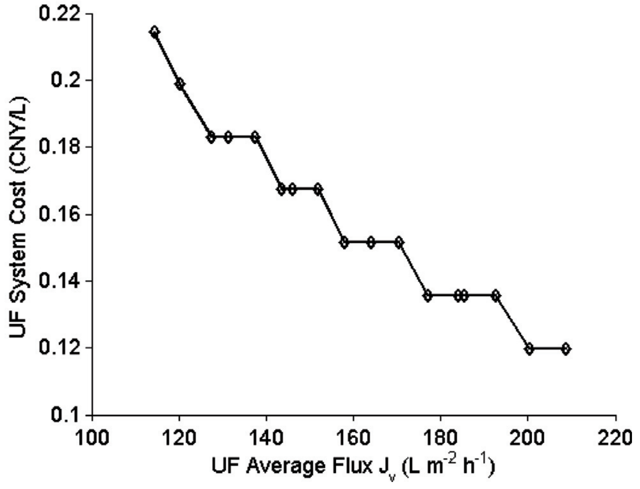


Fig. 6. SSF equipment investment cost vs. UF average flux.

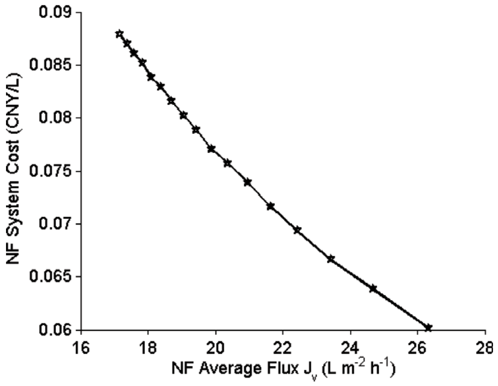
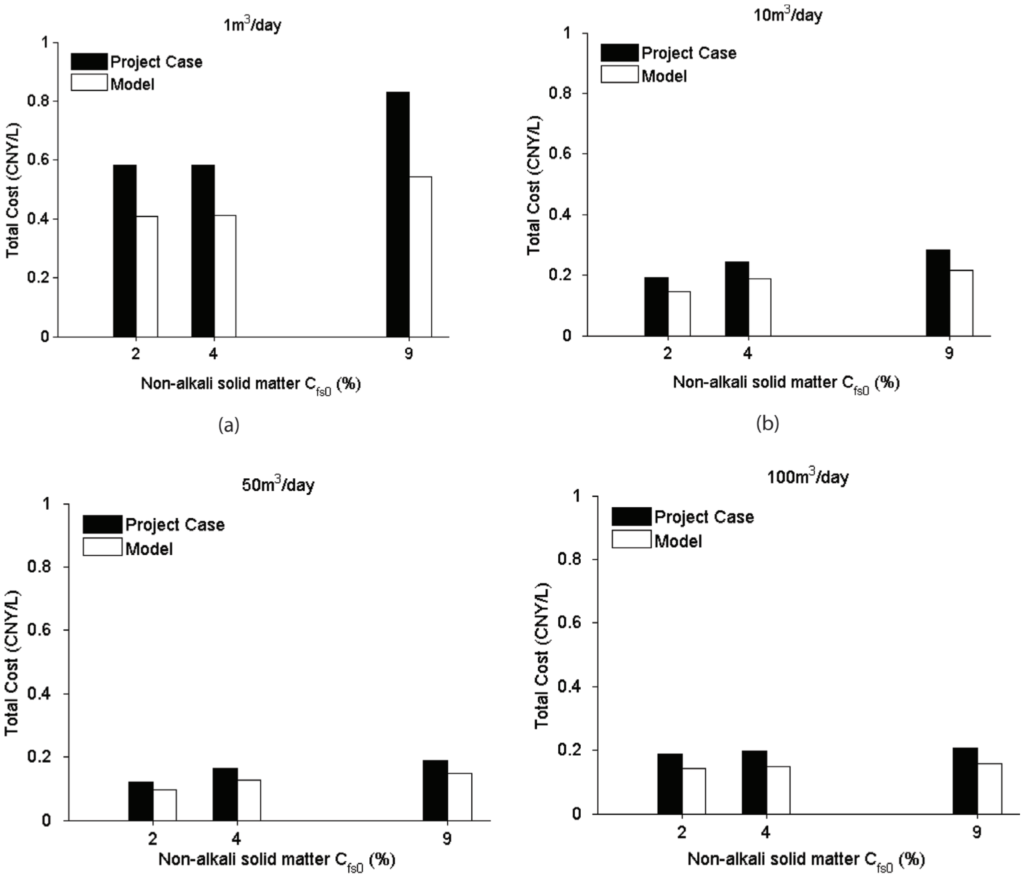


Fig. 7. NF equipment investment cost vs. NF average flux.



(a) (b)

(c) (d)

Fig. 8. Model simulation cost and actual cost under operating time 18 h.

were from 20% to 30%, except the errors at 1 m^3/d capacity and 9% non-alkali solid content was 34.7%. As the investment cost of enterprise computing include the appropriate profit and labor costs, it was acceptable that the actual values were 10% to 30% higher than the model values, which indicated that the economic model can predict the total cost of the process.

4. Conclusions

It indicated that the predicted values were 20% to 30% lower than the actual values and the models were realistic contrasting with the actual and predicted values of CC and OC. Because the relative cost and price of small scale equipment were pretty high, the models' errors were large in the low-capacity condition which shown the economy models were more suitable for large industrial scale production. The longer run, the total costs were significantly decreased at the same processing volume requirements. The larger capacity, the more membrane count, the membrane area utilization was higher, the unit cost of feed more significantly reduced; If little capacity, for instance 1 m^3/d, the total costs and investment costs were significantly high .

The study indicated that the models can predict the cost of recycling of alkali from chitin processing by SSF and the NF process.

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Symbols

A_{mem} — Membrane area, m^2
A_{mod} — The membrane area of each membrane component
A/P — Coefficient of amortization

C_c — Capital cost, CNY/L
C_e — Cost of energy per unit volume of wastewater, CNY/m^3
C_m — Membrane cost
C_{mr} — Membrane replacement cost
C_p — A function of membrane area
c_{chem} — Price of each chemicals, CNY/t
c_{kw} — Price of electricity, CNY/J
c_m — The membrane price CNY/modul
d_{chem} — Dosage of each chemicals, m^3
DL — Design life, year
i_c — Discount rate
i_f — Annual discount rate for membrane replacement, expressed as a decimal fraction
J_m — Average flux, LMH;
k — A constant representing the relative weight of a cost component
ML — Membrane life, years
n — Exponent representing the economy of scale associated with a cost component
n_{mod} — Number of membrane module required
Q_{clean} — Cleaning water amount, m^3
Q_{des} — Total treatment capacity, m^3
Q_{desn} — Capacity of design, m^3
t — Processing time of each work cycle required, hr
t_o — Filtration time, hr

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