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The influence of various operating conditions on specific cake resistance in the crossflow microfiltration of yeast suspensions

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ABSTRACT

In this paper, a multi-regression method was used to study the influence of different operating conditions on the specific cake resistance (SCR) of yeast suspensions in order to optimize the operating conditions in the crossflow microfiltration. The experimental results showed that the crossflow velocity, transmembrane pressure, concentration and temperature had an obvious influence on the SCR. The SCR decreased with the rising temperature, and increased with the increasing crossflow velocity or pressure, and also increased with the increase of the concentration in the range of 1.0–3.0 g/l first and then decreased in the range of 3.0–5.0 g/l. The relative degrees of the influence of the crossflow velocity, concentration, transmembrane pressure and temperature on the SCR of yeast suspensions were 38.85%, 28.32%, 19.34%, and 13.49%, respectively. A reasonably quantitative regression relationship between the SCR (α) and the crossflow velocity (U), transmembrane pressure (P), feed concentration (C) and temperature (T) was obtained as follows: $\alpha = 4.3652\times10^{14}\,U + 1.2256\times10^{15}\,P + 1.8224\times10^{13}\,C - 2.9467\times10^{12}\,T + 1.4704\times10^{14}$.

Keywords: Influence; Operating conditions; SCR; Crossflow microfiltration; Multi-regression method

1. Introduction

Currently, great importance has been attached on the use of the membrane separation technology in the field of separation and purification in biology and chemistry, foodstuff ferment, alcohol and alcohol beverage and so on [1–7]. Especially, as a widely used and the most commonly sold pressure-driving membrane technology, microfiltration is widely used in the food industry, biotechnology, medicine, drinking water purification, wastewater treatment, the petroleum industry, the metallurgical industry and so on [8,9]. It is well known that the most serious operational constraint in its industrial use is the flux decline caused by membrane fouling due to adsorption and blockage of particles into membrane pore and the formation of deposition on the membrane surface and so on [9], which will lead to the change of the total resistance. The specific cake resistance (SCR) is a very important parameter token of cake deposition on the membrane surface, so how to quantificationally calculate the SCR has a great significance.

Since the SCR will be influenced by many factors, such as operating conditions (crossflow velocity, transmembrane pressure, concentration, temperature) [10–21], the particle diameter, particle shape and porosity of cake-layer [22–25], pH [26,27] and ionic strength [28] of feed suspension, and there has been a large number of studies [10–30] on the SCR. However, for the appointed suspensions, such as in the real industrial process, only the operating conditions play an important role on SCR, so there are many literatures in this field and its mainly focused on the following aspects: (i) With the rising

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crossflow velocity, the SCR decreased [10,14], or increased [11,12], or existed a maximum [13] respectively, according to the different mechanism of the cake formation on the membrane surface; (ii) An exponent function can be found between a majority of average SCR of the compressible cake and transmembrane pressure [10–11, 14–18], but the SCR of the incompressible cake was independent on the transmembrane pressure [15]; (iii) The SCR dramatically changed with the suspension concentration. Sometimes the SCR reduced as the suspension concentration increased [14,20], and appeared a maximum SCR value [21], but possibly appeared a minimum SCR value [19,22]. Furthermore, the SCR also changed with the temperature [31]

However, a majority of the literatures primarily focused on the qualitative studies and only few quantitative studies about the interactive effects of different operating conditions on SCR have been found [31]. In contrast, only a quantitative mathematical formula which has certain mathematical independence between the SCR and the different operating conditions can satisfy the real industrial process. So, how to establish the relationship between the SCR and various operating conditions and quantificationally estimate its contribution to SCR has a great significance to gain more theoretical understanding. Therefore, the purpose of this paper is to study interactive effects of the four key experimental parameters on SCR of yeast suspensions and try to build a reasonably quantitative relationship between SCR and various operating conditions by using the multi-regression method.

2. Experimental

2.1. Materials

Polytetrafluoroethylene (PTFE) microfiltration membranes with a nominal pore size of 0.2 μm were used as pre-filtrated medium, which were purchased from Beijing Chemical Engineering University Liming Membrane Material Corporation (Beijing, China). Hydrophilic polyvinylidene fluoride (PVDF) membranes with a nominal pore size of 0.1 μm were used as filtration medium from Ande Membrane Separation Technology Engineering (Bejing) Co.,Ltd.. $Na_2HPO_4{\cdot}12\ H_2O$ and KH_2PO_4 were used as the preparation of phosphate-buffered solutions (PBS) from Beijing YILI fine Chemical Engineering, Ltd.. Mauri instant dry yeast was produced by Harbin-Mauri Yeast Co. Ltd., whose average particle size is 5.1 μm. Before conducting the experiments, the PTFE/PVDF membranes were soaked in deionized water for 24 h to remove glycerin, which was used as a protectant in membranes.

2.2. Experimental equipment

The following equipment was used in this study: WG2003 model Miniature oven was supplied by Chongqing Sida experimental instrument Co. Ltd. SJ9-2 model quartz seconds counter was provided by Shanghai seconds counter factory. HJ-5 model magnetic stirrer was supplied by Jiangsu Ronghua instrument Co. Ltd. with the constant temperature. Electronic balance was provided by Ohaus Corp Ping Brook. NJ with precision of 0.0001 g. LD5-10 model centrifuge was provided by Beijing medical centrifuge factory company. Ultrasonic generator 235 was supplied by academy of science acoustics graduate school. Easy-load II77200-62 model peristaltic pump was provided by Masterflex L/S. MAF-5001model Malvern laser particle diameter distribution instrument (Britain) was used to get the particle diameter distribution of yeast suspensions.

2.3. The preparation of solutions

2.3.1. The preparation of phosphate-buffered solutions (PBS)

Phosphate-buffered solutions (PBS) were prepared by dissolving 0.03 M $Na_2HPO_4{\cdot}12\ H_2O$ and 0.03 M KH_2PO_4 in 1000 ml deionized and pre-filtered water. Then the buffer solutions were filtered using a PTFE MF membrane with a nominal pore size of 0.2 μm at a low pressure (0.01 MPa) to eliminate large or suspended particles.

2.3.2. The preparation of yeast suspensions

The preparation of the dry washed yeast: Mauri instant dry yeast was dissolved into 800 ml deionized water which was prefiltered through a 0.2 μm PTFE membrane at 25°C for 30 min with stirring. After rehydration, the yeast suspension was centrifuged at a speed of 2500 rpm for 10 min, and then the supernatant was removed. The above washing process was repeated three times. After washing, the yeast was dried in the WG2003 model Miniature oven. Dry yeast weight was measured after drying the washed yeast at 80°C for 6 h. The mass was measured again after 6 h to make sure no weight change had occurred. The preparation of yeast suspensions: in order to achieve the desired concentration, a specific amount of dry washed yeast was dissolved into a specific amount of phosphate-buffered solutions (PBS) with firstly stirring for 20 min and then ultrasonic processing for 20 min. Therefore, in this study, all concentrations of yeast suspensions were referred to the concentrations of the dry washed yeast and the yeast suspensions were prepared daily and generally used within 24 h.

2.4. Apparatus and method

The crossflow microfiltration experiments under constant transmembrane pressure mode were carried out in a flat-sheet laboratory-scale MF cell with an effective filtration area of $78.66\times10^{-4}\ m^2$ in different ranges of 0.08–

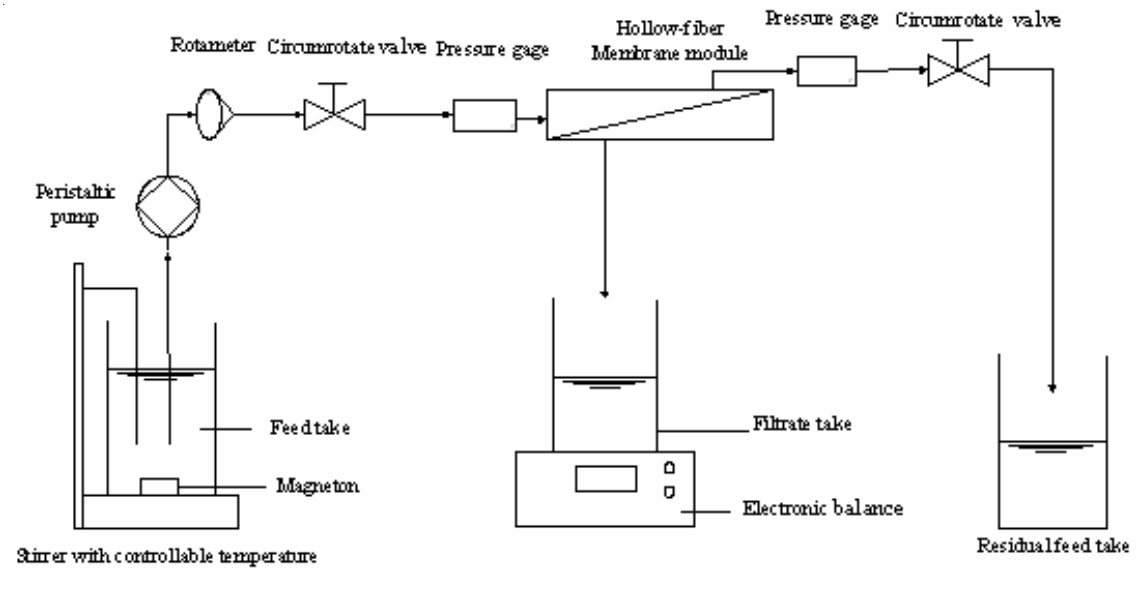

Fig. 1. Schematic diagram of the cross-flow MF setup.

0.3 m/s, 0.02–0.1 MPa, 1.0–5.0 g/l and 20–45°C (Fig. 1). The experimental data were recorded every 30 s.

3. Determination of SCR and analytical model

3.1. Calculation of the average intrinsic membrane resistance

The flux of PVDF microfiltration membrane with 0.1 μm pore size was measured first in the range of 0.02–0.1 MPa and deionized water as feed, then the graph of flux vs. transmembrane pressure was plotted (Fig. 2). Fitting equation of flux vs. pressure was gained:

$$J = 4.5334\times10^{-9}\,\Delta P - 4.7022\times10^{-5}$$

where J = average membrane flux, m/s; ΔP = transmembrane pressure, Pa. Finally, the average intrinsic membrane resistance in the range of 0.02–0.1 MPa was $2.0\times10^{11}\,m^{-1}$ which was calculated on the basis of the fitting equation and Darcy law.

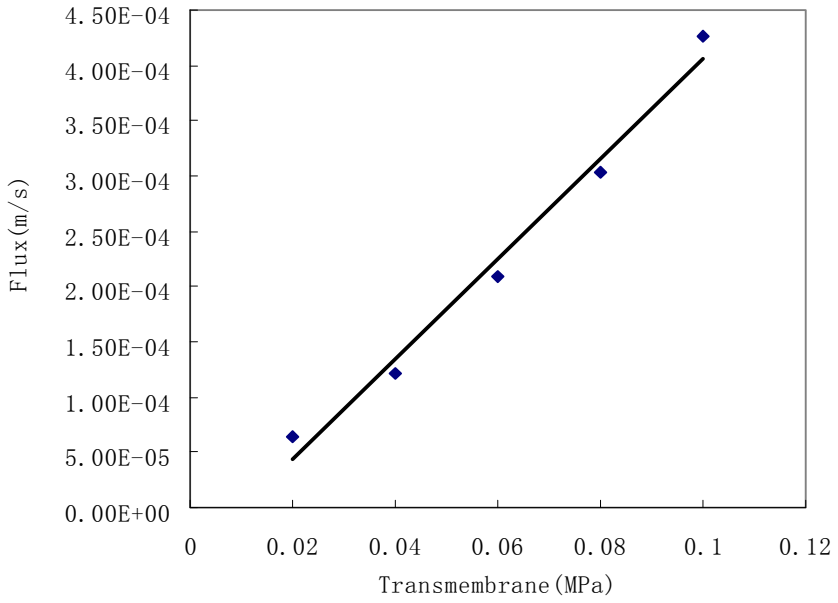

Fig. 2. The flux of the deionized water vs. transmembrane pressure.

3.2. Calculation of the SCR

$$\alpha = \frac{R_c}{M/A_m} = \frac{\frac{\Delta P}{\eta J} - R_m}{M/A_m} \quad (1)$$

where α = the specific cake resistance, m/kg; J = average membrane flux, $m^3/(m^2 \cdot s)$; R_c = cake resistance, m^{-1}; R_m = intrinsic membrane resistance, m^{-1}; η =viscosity, Pa·s; A_m = membrane surface, m^2; M = cake quality on membrane surface, kg; ΔP = transmembrane pressure, Pa.

3.3. Determination of cake mass on the membrane surface

Before experiments, the mass (M_1) of the experimental membrane sample was weighted by the electronic balance with the precision of 0.0001 g. After the experiment, the experimental membrane sample with yeast slurry was dried in an oven at 80°C for 2–3 h until its mass unchanged, then the mass (M_2) of the membrane sample with dry yeast slurry was weighed again. So the cake mass on the membrane surface was obtained by M_2 minus M_1 ($M = M_2 - M_1$).

3.4. Determination of compressibility of the yeast cakes

It is known that most of cakes are compressible. The relation between the specific resistance of the cake and ΔP is represented as follows:

$$\alpha = \alpha_0 \Delta P^n \quad (2)$$

where n is the compressibility exponent which can be found from the slope of line between ln α and ln ΔP. Using above Eq. (2), the compressibility exponent, n, was determined to be 0.23 for yeast suspensions in present crossflow microfiltration. Hence, the yeast cakes were compressible, which would be applied to explain some of the following phenomena.

3.5. Experimental data processing

The crossflow velocity, transmembrane pressure, concentration, temperature and SCR are represented by U_i, P_i, C_i, T_i and α_i, respectively in which i = 1,2,...,n is the sequence number. The experimental data sequences were standardized as follows:

$$BU_i = (U_i - \bar{U})/U_\sigma,\ BP_i = (P_i - \bar{P})/P_\sigma,$$
$$BC_i = (C_i - \bar{C})/C_\sigma,\ BT_i = (T_i - \bar{T})/T_\sigma, \quad (3)$$
$$B\alpha_i = (\alpha_i - \bar{\alpha})/\alpha_\sigma$$

where BU_i, BP_i, BC_i, BT_i and $B\alpha_i$; $\bar{U}$, $\bar{P}$, $\bar{C}$, $\bar{T}$ and $\bar{\alpha}_c$; U_σ, P_σ, C_σ, T_σ and α_σ are the standardized value, the averaged value and the standard deviation of the sequences of crossflow velocity, transmembrane pressure, concentration, temperature and SCR, respectively.

3.6. Analytical model and analytical method

The multi-linear regression analysis was performed by using the standardized experimental data [32], the basic multi-linear regression model was described as follows:

$$B\alpha_c = b_1 BU_i + b_2 BP_i + b_3 BC_i + b_4 BT_i \quad (4)$$

where b_1, b_2, b_3 and b_4 are the regression coefficients of crossflow velocity, transmembrane pressure, concentration, temperature on the SCR, respectively.

By using the regression coefficient of the independent variable on the SCR divided the relative standard error, SCR factors (R_c) were obtained as follows:

$$R_c = b_i / \sigma_j \quad (5)$$

where j is the factor number (j = 1, 2, 3), and the absolute value of a SCR factor that is in excess of 1 is considered as an influential factor. Thus, the influential level of an independent variable on the SCR was estimated according to the absolute value of the SCR factors. SCR factors correlated with a t-distribution of which the number of degrees of freedom was $n - m - 1$ (n is sample size, m is the number of independent variable, if the absolute value of SCR factor is greater than $t_{\alpha,}$ the influential factor is more obvious).

In addition, when b_1, b_2, b_3 and b_4 were all influential factors, the influential degree of the independent variables on SCR was estimated by their percents as follows:

$$B_i = 100 b_i^2 \Big/ \sum_{j=1}^{3} b_j^2 \quad (6)$$

where B_1, B_2, B_3 and B_4 are the SCR percentages of b_1, b_2, b_3 and b_4, respectively.

Under the assumption that b_1, b_2, b_3 and b_4 were all of the influential factors, according to the experimental data of crossflow velocity, transmembrane pressure, concentration, temperature and SCR, the multi-linear regression model of the changing SCR as temperature, transmembrane pressure and concentration was designed as follows:

$$\alpha_{ci} = d_0 + d_1 U_i + d_2 P_i + d_3 C_i + d_4 T_i \quad (7)$$

where d_0 is a constant, d_1, d_2, d_3 and d_4 are the regression coefficients of the crossflow velocity, transmembrane pressure, concentration and temperature on the SCR, respectively.

4. Results and discussion

4.1. Experimental data

Table 1
The schedule of experimental data

No.	Concentration (g/l)	Temperature (°C)	TMP (MPa)	Crossflow velocity (m/s)	SCR ($\times 10^{14}$ m/kg)	Flux ($\times 10^{-5}$ m/s)	Mass of cake kg/m^2
1	2	25	0.02	0.08	1.75	1.36	0.0055
2	2	25	0.04	0.08	1.97	1.64	0.0098
3	2	25	0.06	0.08	2.02	1.20	0.0222
4	2	25	0.08	0.08	2.41	1.07	0.0289
5	2	25	0.1	0.08	2.87	1.22	0.0268
6	2	25	0.06	0.12	2.12	1.00	0.0258
7	2	25	0.06	0.16	2.22	1.26	0.0191
8	2	25	0.06	0.24	2.61	1.47	0.0137
9	2	25	0.06	0.3	3.31	2.16	0.0069
10	2	20	0.06	0.08	2.53	1.38	0.0151
11	2	30	0.06	0.08	1.71	1.14	0.0279
12	2	35	0.06	0.08	1.49	1.05	0.0350
13	2	45	0.06	0.08	1.44	9.58	0.0400
14	1	25	0.06	0.08	1.70	1.38	0.0226
15	3	25	0.06	0.08	2.81	7.01	0.0287
16	4	25	0.06	0.08	2.56	6.48	0.0341
17	5	25	0.06	0.08	2.27	7.70	0.0321
18	3	25	0.02	0.08	2.52	7.14	0.0103
19	3	25	0.04	0.08	2.70	7.20	0.0198
20	3	25	0.08	0.08	3.21	7.12	0.0344
21	3	25	0.1	0.08	3.60	7.67	0.0357
22	3	25	0.06	0.12	3.15	9.18	0.0201
23	3	25	0.06	0.16	3.26	9.08	0.0197
24	3	25	0.06	0.24	3.61	1.07	0.0150
25	3	25	0.06	0.3	3.81	1.06	0.0144
26	3	20	0.06	0.08	2.91	6.59	0.0306
27	3	30	0.06	0.08	2.61	5.53	0.0408
28	3	35	0.06	0.08	2.48	6.18	0.0384
29	3	45	0.06	0.08	2.42	6.76	0.0359
30	4	25	0.02	0.08	2.39	7.20	0.0095
31	4	25	0.04	0.08	2.51	9.06	0.0155
32	4	25	0.08	0.08	2.76	1.04	0.0260
33	4	25	0.1	0.08	3.55	7.65	0.0399
34	4	25	0.06	0.12	2.67	8.78	0.0237
35	4	25	0.06	0.16	2.81	1.03	0.0190
36	4	25	0.06	0.24	3.21	1.22	0.0147
37	4	25	0.06	0.3	3.54	1.12	0.0145
38	4	30	0.06	0.08	2.42	1.17	0.0204
39	4	35	0.06	0.08	2.38	1.32	0.0183
40	4	45	0.06	0.08	2.38	1.41	0.0234
41	5	25	0.02	0.08	1.99	4.07	0.0236
42	5	25	0.04	0.08	2.16	5.28	0.0342

Table 1 (continued)

No.	Concentration (g/l)	Temperature (°C)	TMP (MPa)	Crossflow velocity (m/s)	SCR ($\times 10^{14}$ m/kg)	Flux ($\times 10^{-5}$ m/s)	Mass of cake kg/m^2
43	5	25	0.08	0.08	2.49	5.16	0.0615
44	5	25	0.1	0.08	3.04	5.44	0.0598
45	5	25	0.06	0.12	2.48	7.12	0.0331
46	5	25	0.06	0.16	2.68	7.43	0.0294
47	5	25	0.06	0.24	3.05	9.98	0.0191
48	5	25	0.06	0.3	3.44	1.08	0.0155
49	5	20	0.06	0.08	2.67	4.88	0.0452
50	5	30	0.06	0.08	2.20	5.61	0.0477
51	5	35	0.06	0.08	2.13	6.88	0.0400
52	5	45	0.06	0.08	2.01	8.39	0.0463
53	1	25	0.02	0.08	1.52	7.99	0.0151
54	1	25	0.04	0.08	1.70	1.00	0.0222
55	1	25	0.08	0.08	2.29	1.11	0.0307
56	1	25	0.1	0.08	2.50	1.10	0.0330
57	1	25	0.06	0.12	1.75	1.12	0.0295
58	1	25	0.06	0.16	1.95	1.32	0.0223
59	1	25	0.06	0.24	2.51	1.31	0.0174
60	1	25	0.06	0.3	3.12	1.74	0.0105
61	1	20	0.06	0.08	1.81	1.25	0.0254
62	1	30	0.06	0.08	1.42	1.59	0.0251
63	1	35	0.06	0.08	1.30	1.58	0.0277
64	1	45	0.06	0.08	1.16	1.70	0.0286
65	4	20	0.06	0.08	2.74	1.14	0.0185
66	1.5	25	0.06	0.08	1.99	1.16	0.0234
67	2.5	25	0.06	0.08	2.16	9.81	0.0259

4.2. Particle diameter analysis of yeast suspensions

Particle diameter of yeast suspensions which was tested by MAF-5001model Malvern laser particle diameter distribution instrument (Britain) is described in Fig. 3. It can be seen from Fig. 3 that the average particle diameter is about 4–5 μm which is far larger than 0.1 μm of the average pore size for a microfiltration membrane. Therefore, all particles of yeast suspensions will be intercepted by the membrane and form the cake on the membrane surface during the filtration which belongs to cake filtration.

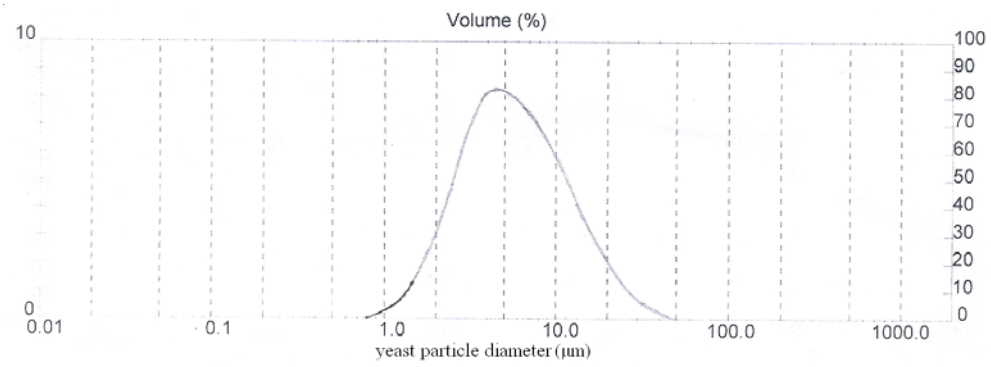

Fig. 3. Particle diameter distribution of yeast suspensions.

4.3. Analysis of influence of different operating conditions on SCR

4.3.1. Impact of concentration

Fig. 4 displays the SCR as a function of concentration under the condition of 0.08 m/s, 0.06 MPa, 25°C, the SCR was gained by Eq. (1). The figure shows that the SCR increased with the increasing concentration in the range of 1.0–3.0 g/l, in contrast, the SCR decreased with the increasing concentration in the range of 3.0–5.0 g/l, which meant that the SCR firstly increased to the maximum and then decreased. The reason was that, before the concentration reached a certain value, the cake porosity would decline due to the less solute particles preferentially entering into cake [33], which finally led to the increased SCR. When the concentration exceeded a certain value, the increase in both bridge of particles and cake porosity caused the reduction of the SCR. The experimental result was consistent with what was shown in the literature [18,21], so the appropriate concentration which less than a certain value should be kept during the industrial membrane filtration process.

4.3.2. Impact of crossflow velocity

In Fig. 5, the effect of the crossflow velocity on SCR for yeast suspensions calculated in terms of Eq. (1) is described under the conditions of 0.06 MPa, 25°C. Obviously, it can be seen that the SCR increases as the increasing crossflow velocity for each concentration in the crossflow velocity range of 0.08–0.3m/s. In general, the higher crossflow velocity causes the bigger drag force and the shear force for solute particles, and backward transfer rate of solute particles to bulk suspension is also higher, so a majority of bigger solute particles are carried back into bulk suspension and smaller particles deposited on the membrane surface to make the formed cake more compact. In addition, the boundary layer thickness of the laminar flow is thinned and the deposition of solute particles on the membrane surface is restrained [34]. Hence, the SCR increased with the increasing crossflow velocity, which was in accordance with the result in the literature [11]. Additionally, the following change trend was found in Fig. 5: in the concentration range of 1.0–2.0 g/l, the increasing trend slowed down in the range of 0.08–0.16 m/s, whereas the trend speeded up quickly in the range of 0.16–0.3 m/s. In the concentration range of 3.0–5.0 g/l, the SCR almost lineary rose in the whole crossflow velocity range.

4.3.3. Impact of pressure

The result in Fig. 6 indicate that the SCR for yeast suspensions in terms of Eq. (1) increased with the increase in the transmembrane pressure in the range of 0.02–0.1 MPa for each concentration under the same condition of 0.08 m/s, 25°C. It can be considered that the porosity of compressible cake [14,35] reduces due to the rearrangement and transmutation of solid particles or the fracture of coacervate with the transmembrane pressure increasing, so the SCR will increase. On the one hand, in the range of 0.02–0.06 MPa, the sedimentation rate of solute particles for yeast suspensions in the membrane module is lower, sedimentation mass is smaller, so the SCR slowly increases with transmembrane pressure rising. On the other hand, in the range of 0.06–0.1MPa, the increase in the transmembrane pressure induces obvious sedimentation of solute particles for yeast

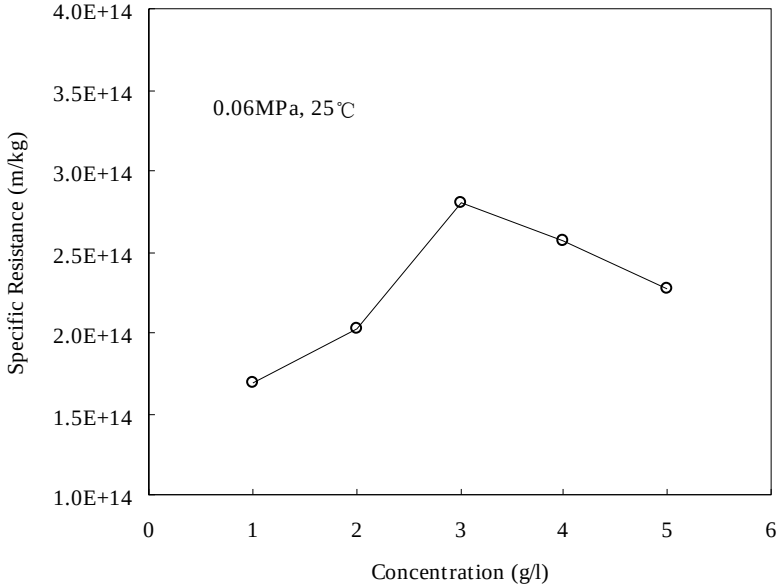

Fig. 4. The SCR of yeast suspensions vs. concentration.

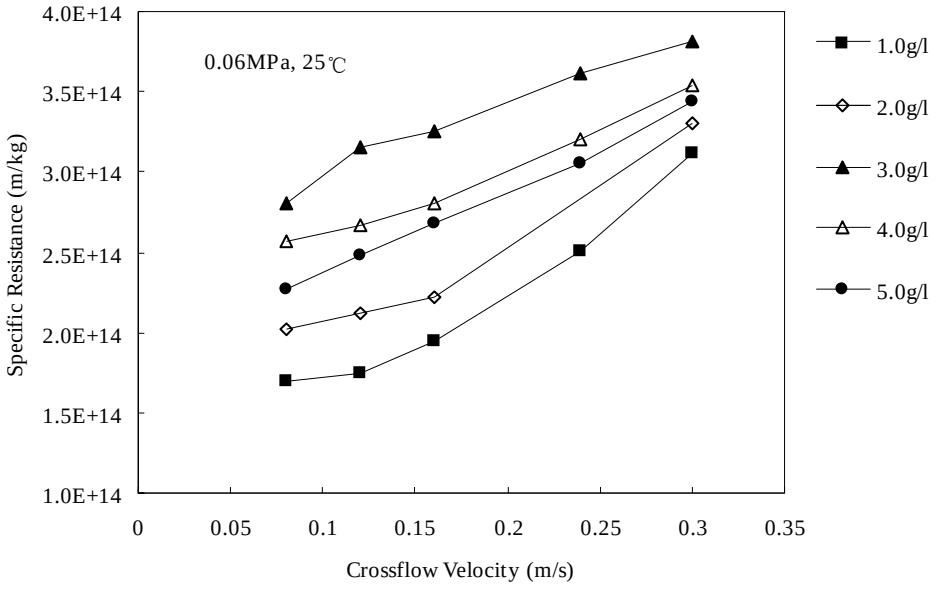

Fig. 5. Change of SCR for yeast suspensions as crossflow velocity.

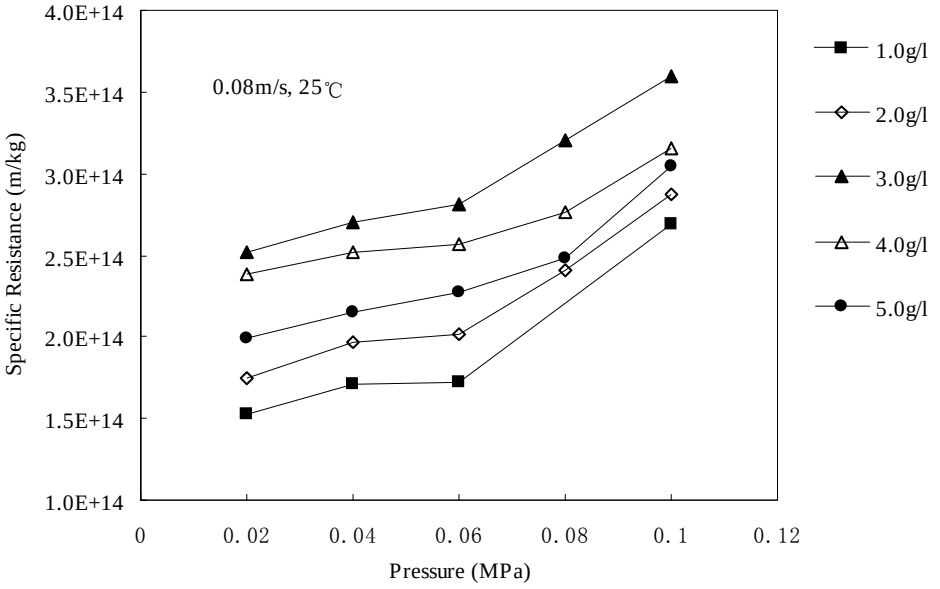

Fig. 6. Variation of the SCR for yeast suspensions with pressure.

suspensions in the membrane module, and moreover, the smaller solute particles deposit easily in the membrane module, which causes the cake thicker and more compact. Hence the SCR increased sharply with rising transmembrane pressure.

4.3.4. Effect of temperature

The change of the specific cake resistance of 1.0 g/l, 3.0 g/l, 4.0 g/l, 5.0 g/l in response to different temperatures on the basis of Eq. (1) is presented in Fig. 7 under the conditions of 0.08 m/s, 0.06 MPa, respectively. It can be seen from Fig. 7 that the SCR reduces with the rising temperature for each concentration. However, the decreasing trend in the SCR was different in different ranges of concentrations, the SCR decreased slowly for the concentrations of 1.0 g/l, 3.0 g/l, 4.0 g/l, 5.0 g/l with the rising temperature, while declined for the concentration of 2.0 g/l dramatically. The reason is explained as follows: the higher temperature causes the lower viscosity, which

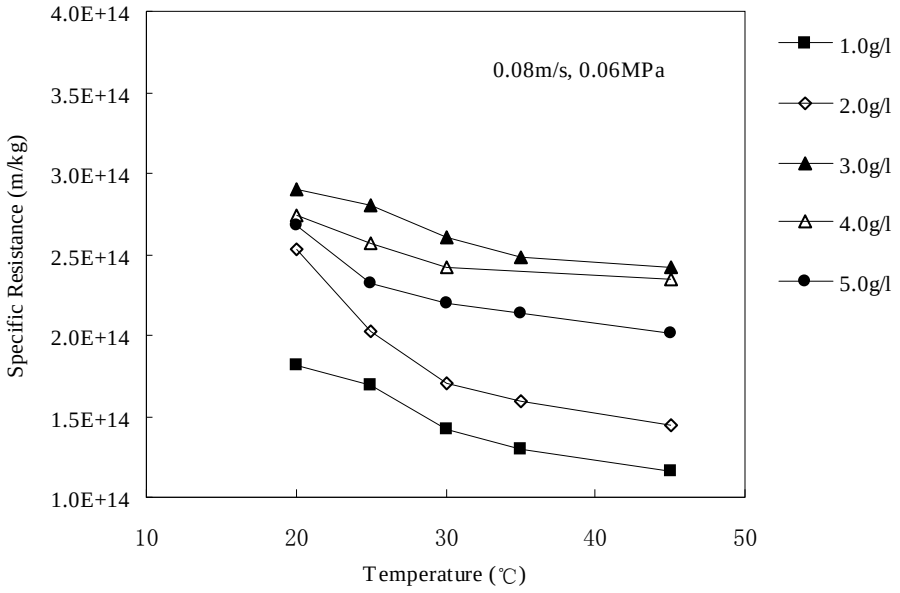

Fig. 7. The SCR for yeast suspensions in response to temperature.

accelerates the liquid flow [36], makes the drag force for solute particles to increase and the bridge phenomena become insignificant, at the same time, the strength of solute molecules movement in the yeast suspensions causes the rise of diffusion coefficient and mass transfer coefficient. As a result, solute particles of yeast suspensions deposit uneasily on the membrane surface and the formed cake becomes looser. So the lower is the temperature, the higher is the SCR.

4.4. Influence degree of specific resistance

In terms of Eqs. (3)–(7), degrees of effect of influence factors on SCR for yeast suspensions are shown in Table 2. It is obvious from Table 2 that the crossflow velocity, transmembrane pressure, concentration and temperature are all remarkable influential factors due to $|R_1| > |R_3| > |R_2| > |R_4| > t_{0.05}(62) > 1$. Furthermore, because $R_1 = 6.8865$, $R_2 = 4.9619$, $R_3 = 6.0031$, the crossflow velocity, transmembrane pressure and concentration have significant positive contributions to SCR. However, because $R_4 = -4.0587$, the temperature have an obvious negative effect on it. Therefore, the result gained by using the multi-regression model is consistent with that of 4.3. Additionally owing to B_1 (38.85%) > B_3 (28.32%) > B_2 (19.34%) > B_4 (13.49%), the sequence of influence degrees of crossflow velocity, transmembrane pressure, concentration and temperature on SCR is crossflow velocity > concentration > pressure > temperature.

Table 2
Analysis of influence factors

i	b_i	R_i	B_i (%)	n	m	$t_{0.05}(57) \approx z_{0.05}$
1	0.4940	6.8865	38.85	62	4	1.645
2	0.3485	4.9619	19.34			
3	0.4217	6.0031	28.32			
4	–0.2911	–4.0587	13.49			

4.5. Variance analysis and test of the multi-regression model

The variance analysis of the multi-regression model was obtained to test whether the whole multi-regression process is remarkable (Table 3). It was testified that the total regression process is significantly remarkable owing to $F = 34.9208 > F_{0.05}(4,63) = 2.04$. Hence, using the experimental data of U_i, P_i, C_i, T_i and α_{ci}, the regression relationship between crossflow velocity, transmembrane pressure, concentration, temperature and SCR can be built as follows on the basis of Eq. (7):

$$\alpha = 4.3652\times10^{14}U + 1.2256\times10^{15}P + 1.8224\times10^{13}C - 2.9467\times10^{12}T + 1.4704\times10^{14} \quad (8)$$

where α = specific cake resistance, m/kg; U = crossflow velocity, m/s; P = pressure, MPa; C = concentration, g/l; T = temperature, °C. The coefficient of correlation between the calculated SCR value and the experimental SCR value was 0.8302, so throughout the whole range of temperatures and transmembrane pressures, the experimental values accorded well with the theoretical values calculated by Eq. (8). In addition, the relative absolute error was used as a testing index. Five experiments which were not used to build the multi-regression model in the experimental rang were performed to validate the avail-

Table 3
Variance analysis of the multi-regression model

Source	Degrees of freedom	Sum of squares	Mean square	F	$F_{0.05}$ (4,58)
Regression analysis	4	45.4852	11.3713	34.9208	2.04
Residual	58	20.5148	0.3156		
Total	62	61			

Table 4
The comparison of the experimental value and the modeling value

No.	C (g/l)	T (°)	P (MPa)	U (m/s)	Experimental value ($\times 10^{14}$ m/kg)	Modeling value ($\times 10^{14}$ m/kg)	Relative error (%)	Arithmetic average value (%)
1	1.5	25	0.06	0.08	1.99	2.09	5.03	
2	2.5	25	0.06	0.08	2.16	2.27	5.09	
3	4.0	35	0.06	0.08	2.38	2.25	–5.46	3.03
4	2	25	0.06	0.24	2.22	2.53	13.96	
5	1.0	25	0.08	0.08	2.29	2.25	–1.75	

ability of the multi-regression model. The results are shown in Table 4. The average relative absolute error was less than 3.03%. Therefore, the predicting multi-regression model was available.

5. Conclusion

A reasonable analysis result of the standard factors that effect SCR was obtained by using regression coefficients on the basis of a multi-regression model, then the influence of various operating conditions on SCR during the crossflow microfiltration of yeast suspensions was studied according to the size and orientation of the specific cake resistance factors and independent variable coefficients. The SCR increased with the increasing crossflow velocity and pressure. At first, it increased with the increase of the concentration in the range of 1.0–3.0 g/l, and then it decreased in the range of 3.0–5.0 g/l, while it decreased with the increasing temperature. The degrees of influence of crossflow velocity, transmembrane pressure, concentration and temperature on SCR were 38.85%, 28.32%, 19.34%, 13.49%, respectively. Therefore, the influence of crossflow velocity deserves prior attention, which is followed by concentration, transmembrane pressure and temperature during the actual membrane filtration process.

In conclusion, in the ranges of the crossflow velocities (0.08–0.3 m/s), transmembrane pressures (0.02–0.1 MPa), concentrations (1.0–5.0 g/l) and temperatures (20–45°C), a quantitative regression relationship of the SCR in response to crossflow velocity, pressure, concentration and temperature was written as $\alpha = 4.3652\times10^{14}\,U + 1.2256\times10^{15}\,P + 1.8224\times10^{13}\,C - 2.9467\times10^{12}\,T + 1.4704\times10^{14}$. The coefficient of correlation between the calculated SCR value by using the regression relationship and the experimental SCR value was 0.8302, the predicting arithmetic relative error was less than 3.03%.

To sum up the above, all these will be expected to optimize the operational conditions during the practical crossflow microfiltration process.

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