Available online at www.sciencedirect.com
SciVerse ScienceDirect
Energy Procedia 16 (2012) 1066 – 1071
Energy Procedia

2012 International Conference on Future Energy, Environment and Materials

Prediction of Energy Microalgae Production under Flue Gas Using Response Surface Methodology

Lingling Wang, Bingtao Zhao*, Yixin Zhang

School of Energy and Power Engineering, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China

Abstract

Biofixation of CO_2 by microalgae has become an effective carbon dioxide capture and storage (CCS) technology and it has the potential for large-scale application in decreasing CO_2 emission from combustion flue gases. In general, the production of the microalgae under flue gas CO_2 carbon sequestration is closely related with the algae species, culture methods, biological conditions, gas conditions and the CO_2 concentration. In this paper, the production parameter (biomass) for microalgae chlorella under flue gas was predicted using response surface methodology. It was found that the model agreed well with the experimental data. Further, the interacted analysis indicated that the carbon source, nitrogen source, cell inoculation density and light intensity had important effect on microalgae production.

Keywords: Microalgae biomass; production; response surface methodology; flue gas

1. Introduction

Many studies by other experts indicate that biofixation of CO_2 by microalgae is an effective carbon dioxide capture and storage technology. Many scholars at domestic and foreign had studied the breeding conditions, growth characteristics and the influence factors of microalgae, and had achieved a significant progress [1]. But these studies design experiments based on single factor mostly, in the other word, they studied the microalgae growth on the effect of a parameter under the other factors in the invariable conditions. So it is difficult to determine the interacted relationship between each factor. Recently response surface methodology (RSM) in the experimental design has been more and more attended in

* Corresponding author. Tel.: +86 21 55272740; fax: +86 21 55273704.
E-mail address: zhaobingtao@usst.edu.cn (B. Zhao).

 doi:10.1016/j.egypro.2012.01.170

science and engineering. Designing experiments using RSM can study the influence of various parameters effectively through the statistical methods system [2-3]. In this paper, six main factors, initial inoculation microalgae density, C source concentration, N source concentration, aeration rate, light intensity and temperature, were selected to establish the model for predicting the microalgae biomass. Moreover, the interacted effect of these factors were analyzed and discussed.

2. Modeling biomass production based on RSM

2.1. Basic principle of RSM

In recent years, response surface design is an effective data processing method used in the design of experiments to deal with multi variables effect based on the mathematical statistics theory. It is originally used in physical experiment field to explore science and engineering problems such as simulation optimization, parameter configuration, observation design etc. The greatest merit is that it can be used to determine the nonlinear relationship between the independent variables and dependent variables, and to analyze the interactive effects of independent variables on dependent variables.

Usually, a complete RSM model including constant, linear, interacted, squared terms can be expressed as:

$$Y = \beta_0 + \sum_{i-1}^{k} \beta_i X_i + \sum_{i-1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \beta_{ij} X_i X_j + e(X_1, X_2, \cdots,\ X_k) \tag{1}$$

β_0 is the regression constant, β_i , β_{ii} and β_{ij} are the regression coefficient, e is the random error.

2.2. Variable selection

Usually, microalgae biomass production is considered merely with the light intensity L. Actually, however, under the flue gas situation the microalgae biomass (B) is related with multi factors beside L. In this paper, more influence factors including initial inoculation microalgae density D (g/L), C source concentration C (%v/v), N source concentration N (mg/ L), aeration rate A(vvm), light intensity L(μ E/(m2·s)) and culture temperature T(℃) were selected as independent variables. It can be expressed as:

$$B = f(D, C, N, A, L, T) \tag{2}$$

2.3. Dataset

A dataset with 69 samples was selected to model the special growth rate of microalgae. The properties of the independent variables are listed in Table 1. For the purpose of data processing conveniently all data was normalized within the range of 0-1. The normalized predicted result was finally renormalized for comparison.

Table 1. Properties of the data samples

	Independent Variables						Dependant Variables			Ref
	D	C	N	A	L	T	B1	B2	B3	
Minimum	0.01	0.038	2.26	0.0375	24	18	0.024	0.025	0.03	[4-15]
Maximum	0.45	70	693	2	980	40	0.95	1.609	2.9	

3. Result and Analysis

3.1. Regression equation

Microalgae growth is usually after 4 stages, namely delay phase, logarithmic growth phase, stationary phase and recession phase. The logarithmic growth phase was usually studied by researchers as the third day's biomass. The regression coefficients of the microalgae biomass at the third day based on the statistical theory are listed in the table 2. In the table it is found that the P value is reduced by the increasing of the T value. Little P value declares that this factor's effect is notable. If the P value is greater than 0.05, it means that the influence on objective function by this factor is not significant. There are 9 terms of 28 terms in all have significantly influence on objective function, including 2 linear terms such as *C* and *N,* 3 square terms *D*D* , *T*T* and *A*A,* and 4 cross terms *N*A, N*T, A*T,* and *L*A.* So that the effect of initial inoculation microalgae density, *N* source concentration and aeration rate is significant, and there is a significant interaction influence. In addition, the interaction influenced by temperature and other factors is significant as well.

Table 2. Effect examinations of coded factors

Terms	Coefficient	Standard deviation coefficient	T	P	Terms	Coefficient	Standard deviation coefficient	T	P
Constant	1.05447	5.0932	0.207	0.837	D*N	-0.97166	3.8697	-0.251	0.803
D	0.93263	8.555	0.109	0.914	D*A	0.32211	4.7627	0.068	0.946
C	-1.67938	0.8397	-2	0.052	D*L	0.46447	3.181	0.146	0.885
N	-3.00928	3.3742	-0.892	0.378	D*T	-0.18926	25.0769	-0.008	0.994
A	-1.22265	3.8205	-0.32	0.751	C*N	0.28709	0.4849	0.592	0.557
L	-0.14125	1.6143	-0.087	0.931	C*A	-0.08826	0.5014	-0.176	0.861
T	0.93246	1.4237	0.07	0.945	C*L	-0.99748	1.6634	-0.6	0.552
D*D	0.18603	0.6284	0.131	0.897	C*T	0.25866	1.1617	0.223	0.825
C*C	-0.67386	0.2139	-3.151	0.003	N*A	-3.32126	3.4383	-0.966	0.34
N*N	-0.20096	1.0624	-0.189	0.851	N*L	-0.81719	1.1203	-0.729	0.47
A*A	-2.64521	1.4015	-1.887	0.066	N*T	-6.97897	3.9912	-1.749	0.088
L*L	1.28957	1.2989	0.993	0.327	A*L	-1.41255	0.9728	-1.452	0.154
T*T	-0.73023	0.3328	-2.194	0.034	A*T	8.72311	4.5963	1.898	0.065
D*C	0.32662	1.633	0.2	0.842	L*T	2.17175	4.3713	0.497	0.622

Coefficient of determination R^2 is selected as evaluation parameters. According to the regression result, the correlation coefficient of the microalgae biomass of the third day is 93.35% , the result is ideal. The final result of the 3 days biomass are as follow:

$$\begin{aligned}B_1 &= 25.7066\text{-}162.929X_1 \text{-}0.00646065X_2 + 0.0254297X_3\text{-}3.95309X_4\text{-}0.0120111X_5\text{-}1.01313X_6 + 15.3737X_1^2\text{-}1.86199\text{E-}05X_2^2 \\ &\text{-}5.86671\text{E-}06X_3^2\text{-}0.154901X_4^2\text{-}2.57176\text{E-}06X_5^2 \text{-}5.96256\text{E-}04X_6^2 + 0.00443736X_1X_2\text{-}0.0293294X_1X_3 + 10.5959X_1X_4 \\ &\text{-}0.0160952X_1X_5 + 6.40749X_1X_6 + 2.15702\text{E-}06X_2X_3 + 0.000691989X_2X_4\text{-}2.04838\text{E-}05X_2X_5 + 0.000234844X_2X_6 \\ &\text{-}0.00304296X_3X_4 + 3.31912\text{E-}06X_3X_5\text{-}6.40182\text{E-}04X_3X_6\text{-}1.77480\text{E-}06X_4X_5 + 0.137081X_4X_6 + 0.000592355X_5X_6\end{aligned} \tag{3}$$

$$\begin{aligned}B_2 &= 19.7868\text{-}118.155X_1\text{-}0.00546163X_2\text{+}0.0406131X_3\text{-}14.9235X_4\text{-}0.0136941X_5\text{-}0.708457X_6 + 16.4947X_1^2\text{-}3.00005\text{E-}04X_2^2 \\ &\text{-}7.01277\text{E-}06X_3^2\text{-}3.15811X_4^2\text{+}6.42142\text{E-}08X_5^2\text{-}0.00581117X_6^2 + 0.0327894X_1X_2\text{-}0.0257759X_1X_3 + 8.37612X_1X_4 \\ &\text{-}0.0142741X_1X_5 + 4.69644X_1X_6 + 1.34189\text{E-}05X_2X_3 + 0.000112855X_2X_4\text{-}3.53557\text{E-}05X_2X_5 + 0.000207754X_2X_6 \\ &\text{-}0.00525740X_3X_4\text{+}1.20790\text{E-}06X_3X_5\text{-}0.00113671X_3X_6\text{-}0.00360015X_4X_5 + 0.826312X_4X_6 + 0.000662547X_5X_6\end{aligned} \tag{4}$$

$$
\begin{aligned}
B_3 =\ & 1.55285+3.96109X_1\text{-}0.0143890X_2+0.0603098X_3\text{-}14.4196X_4\text{-}0.012078X_5+0.0371852X_6+3.84350X_1^2\text{-}5.50692\text{E-}04X_2^2 \\
& \text{-}1.68477\text{E-}06X_3^2\text{-}2.74727X_4^2+5.64405\text{E-}06X_5^2\text{-}0.00603494X_6^2+0.0424415X_1X_2\text{-}0.0127881X_1X_3+1.49210X_1X_4 \\
& +0.00441683X_1X_5\text{-}0.0782049X_1X_6+2.37627\text{E-}05X_2X_3\text{-}0.00257132X_2X_4\text{-}5.96545\text{E-}05X_2X_5+0.000672206X_2X_6 \\
& \text{-}0.00980029X_3X_4\text{-}4.95008\text{E-}06X_3X_5\text{-}0.00183702X_3X_6\text{-}0.00301159X_4X_5+0.808163X_4X_6+0.000413038X_5X_6
\end{aligned} \qquad (5)
$$

3.2. Interacted effect

The interactive effects of these 6 factors mentioned above are illustrated in Fig.1 to Fig. 15.

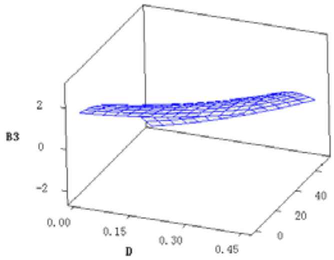

Fig.1. *D* and *C* interactive effect

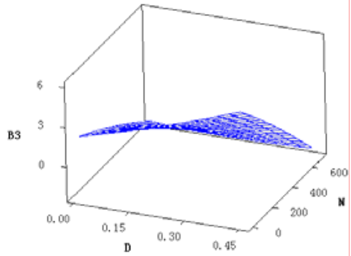

Fig.2 *D* and *N* interactive effect

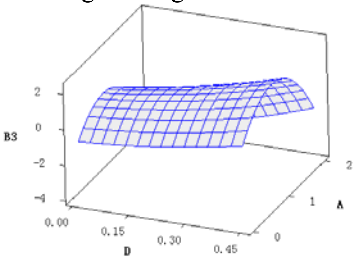

Fig. 3 *D* and *A* interactive effect

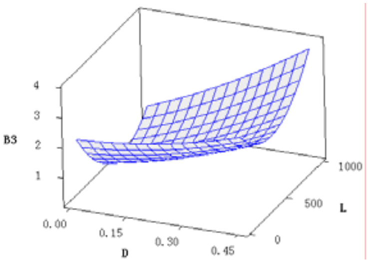

Fig.4 D and L interactive effect

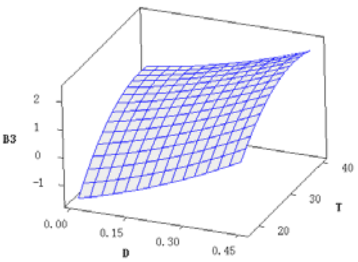

Fig.5 D and T interactive effect

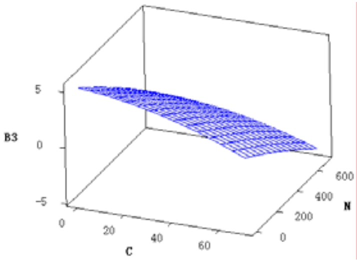

Fig.6 C and N interactive effect

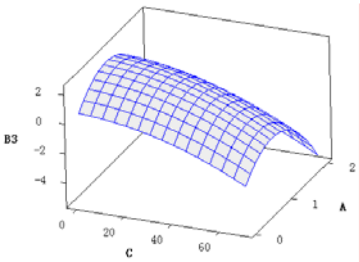

Fig. 7 C and A interactive effect

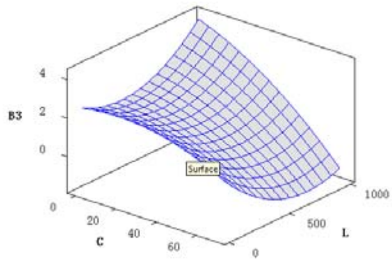

Fig. 8 C and L interactive effect

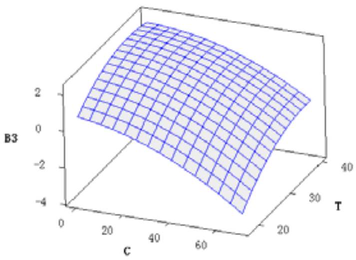

Fig. 9 C and T interactive effect

Fig. 1 shows that microalgae biomass is high cultured in high initial vaccination density, and the microalgae with high initial vaccination will have a strong tolerance in high CO_2 density environment. So a conclusion was obtained that higher CO_2 density can be accessed in higher initial vaccination density cultivation. Fig. 2 shows that microalgae will have a high production in high initial inoculation density and low nitrogen concentration. From Fig. 3 it shows that the environment with high initial vaccination density and the appropriate aeration rate will be good for microalgae growth. Fig. 5 shows that the biomass production is high at the temperature in the range of 20℃ to 30℃. It will against the growth of microalgae under too low or too high temperature. From Fig. 6 it shows that the production of microalgae will be high in low CO_2 density (<10%v/v) and relatively low N source density (<200mg/L) stage, because higher density of CO_2 and N source will make solution pH value reduced, so that the growth of chlorella will be restrained. Fig. 7 shows that the microalgae cultivated in low CO_2 density and an appropriate aeration rate situations will have a high production. Fig. 8 shows that microalgae grows well when light intensity is strong in low CO_2 density stage. From Fig. 10 it shows that under the situation of high aeration rate and low N source density, the microalgae biomass will be high. However, in high N source density situations, along with the increase of aeration rate, biomass increased at first, but decreased later. In general the best aeration rate for microalgae is around 1vvm. Fig. 12 shows that the effect of N source density is quite contrary in low temperature and high temperature stage. The microalgae production will increase along with the increase of N source density when temperature is less than 20℃, but it will be decreased when temperature is more than 40℃. From Fig 13 it shows that microalgae grows well when the aeration rate is at about 1vvm. From Fig. 14 it shows that the biomass will decrease along with the increase of aeration rate when temperature is less than 20℃, because high aeration rate makes microalgae photosynthesis weak. But it will be increased when temperature is more than 30℃. Fig. 15 shows that the effect of light intensity is also quite contrary in low temperature and high temperature stage. The biomass will increase along with the increase of light intensity when temperature is more than 30℃, but it will be decreased when temperature is less than 20℃.

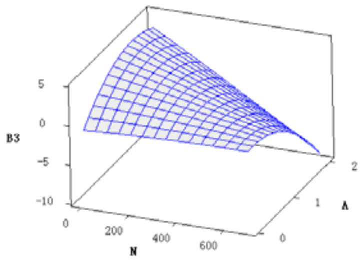

Fig. 10 N and A interactive effect

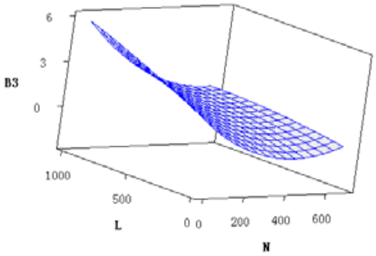

Fig. 11 N and L interactive effect

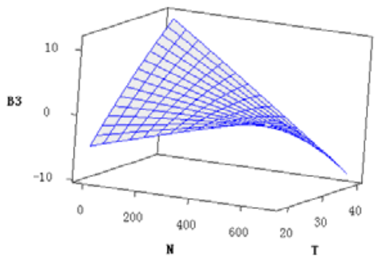

Fig. 12 N and T interactive effect

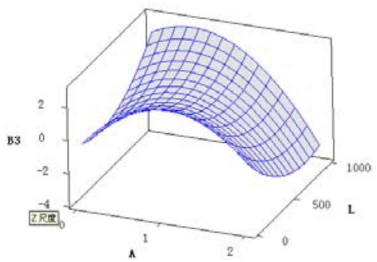

Fig. 13 A and L interactive effect

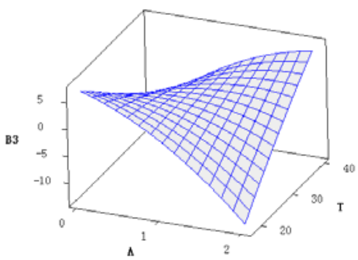

Fig. 14 A and T interactive effect

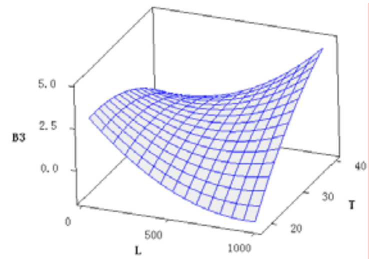

Fig. 15 L and T interactive effect

4. Conclusions

(1) In this paper, a RSM model was established, and a good prediction model was obtained.

(2) The result shows that the interactive effects of N source and aeration rate, N source and temperature, aeration rate and temperature, aeration rate and light intensity were significant.

(3) Temperature is one of the most important factors affecting microalgae growth, and it will affect other factor's role of microalgae growth, such as N source, light intensity and aeration rate will be

restricted by temperature. Chlorella showed a good growth situation from the temperature of 25°C to 35°C, because it can get high biological quality and high chlorophyll content well.

(4) If the more factors are considered, the more complex characteristic of microalgae growth is. It is difficult to design optimization model.

Acknowledgement

This work was jointly supported by National Natural Science Foundation of China (No.50806049) and Innovation Program of Shanghai Municipal Education Commission (No.09YZ209).

References

[1] Norihide Kurano, Shigetoh Miyachi.Selection of Microalgal Growth Model for Describing Specific Growth Rate-Light Response Using Extended Information Criterion. *Bioscience and Bioengineering*.2005;100:403-405.

[2] Wächter R, Cordery A. Response surface methodology modeling of diamond-like carbon film deposition. *J Carbon*，1999; 37:1529-1537.

[3] Zhao Jian-zhi，Lu Duan-feng. Study on Capture Efficiency of PM10 From Coal Combustion in High Gradient Magnetic Field Using Response Surface Methodology. *Proceedings of the CSEE*. 2009; 29: 74-79.

[4] Chiu Sheng-Yi, Kao Chien-Ya, Chen Chiun-Haun,Kuan Tang-Ching, Ong Seow-Chin, Lin Chih-Sheng. Reduction of CO2 by a high−density culture of *Chlorella sp.* in a semicontinuous photobioreactor. *Bioresour Technol*. 2008; 99:3389-3396.

[5] Degen Jorg, Uebele Andrea, Retze Axel, Schmid-Staiger Urlike, Trosh Walter. A novel air-lift photobioreactor with baffles for improved light utilization through the flashing effect. *Biotechnol*. 2001 ; 92 :89-94.

[6] de Morais MicheleGreque, Costa JorgeAlbertoVieira. Biofixation of carbon dioxide by *Spirulina sp.* and *Scenedesmus obliquus* cultivated in a three-stage serial tubular photobioreactor. *Biotechnol*. 2007(a); 129:439-445.

[7] Sung KiDon, Lee Jin-Suk, Shin Chul-Seung, Park Soon-Chul, Choi Myung-Jae. CO_2 fixation by *Chlorella sp. KR-1* and its cultural characteristics. *Bioresour Technol*. 1999; 68:269-273.

[8] Yue Lihong, Chen Weigong. Isolation and determination of cultural characteristics of a new highly CO_2 tolerant fresh water microalgae. *Energy Convers Manage*. 2005 ; 46 : 1868-1876.

[9] Watanabe Yoshitomo, Saiki Hiroshi. Development of a photobioreactor incorporating *Chlorella sp.* for removal of CO_2 in stack gas. *Energy Convers Manage*. 1997 ; 38(Suppl.):499-503.

[10] de Morais, M.G., Costa, JAV. Isolation and selection of microalgae from coal fired thermoelectric power plant for biofixation of carbon dioxide. *Energy Convers Manage*. 2007(b); 48: 2169-2173.

[11]Yoshihara Ken-Ichi, Nagase Hiroyasu, Eguchi Kaoru, Hirata Kazumasa, Miyamoto Kazuhisa. Biological elimination of nitric oxide and carbon dioxide from flue gas by marine microalga NOA-113 cultivated in a long tubular photobioreactor. *Ferment. Bioeng.* 1996 ; 82 :351-354.

[12] Yun Yeoung-Sang, Park Jong-Moon, Yang Ji-Won. Enhancement of CO_2 tolerance of chlorella vulgaris by gradual increase of CO_2 concentration. *Biotechnology Techniques*. 1996; 10: 713-716.

[13] Yue Lihong, Chen Baozhi. Research on optical micro-fixed CO_2.2002.

[14] Anna L Stephenson，John S Dennis，Christopher J Howe，Stuart A Scott，Alison G Smith. Influence of nitrogen-limitation regime on the production by Chlorella vulgaris of lipids for biodiesel feedstocks. *Biofuels*.2010; 1: 47-58.

[15] Jian-Ming Lv，Li-Hua Cheng，Xin-Hua Xu，Lin Zhang，Huan-Lin Chen. Enhanced lipid production of *Chlorella vulgaris* by adjustment of cultivation conditions. *Bioresource Technology*.2010;101:6797-6804.