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Improvement of quality and yield of *Schisandra* oil by controlling vacuum degree during molecular distillation using variable universe fuzzy PID method

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Abstract: By supercritical fluid extraction *Schisandra* crude oil as raw materials for the experiment, the multistage distributed of *Schisandra* oil purification experiment was carried out in molecular distillation system. The relationship between processing parameters and product index of molecular distillation experiment were discussed, furtherly the vacuum degree mathematical model of molecular distillation was established. Because the molecular distillation control system had the characteristics of nonlinear, pure lag and time-varying, in view of the traditional PID control and fuzzy PID control, it was difficult to meet the control requirements. This study proposed the use of variable universe fuzzy PID algorithm to realize the molecular distillation vacuum fixed value control, by introducing a variable domain contraction and expansion factor. The parameters of PID controller and fuzzy threshold for online adjustment, the quantization factor and scaling factor fuzzy controller were carried on the dynamic adjustment, so as to improve the control precision. The results showed that the fuzzy PID control method had better stability and adaptability, and the control method can effectively improve the quality and yield of *Schisandra* essential oil.

Keywords: variable universe fuzzy PID; parameter optimization; molecular distillation; vacuum control; *Schisandra* oil

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Schisandra (Wuweizi, Chinese Magnoliavine Fruit) is a traditional Chinese medicine, which was firstly recorded in the ancient pharmaceutical book "Shen Nong Ben Tsao Ching" as an excellent drug[1]. *Schisandra* oil is commonly used in traditional medicine, which is considered to be one of the 50 fundamental herb medicines. In records of traditional Chinese medicine, it also called magnolia berry or five-flavor-fruit, being reported to have functions as notifying and supporting body fluid, replenishing the kidney and soothing the lung for the treatment of fatigue, chronic cough, enuresis, respiratory disease, diabetes, arrhythmias and other heart diseases[2-3].

Since the molecular distillation technology was created in 1930s, it has been used widely in the oil industry[4-5], medical industry[6], food products[7], fine chemical industry and others[8-9]. It is based on the evaporation of the components of a mixture in the form of a falling film, and in contact with a heated surface and following condensation on a close cold surface[10]. As shown in Fig. 1, after the feedstock enters in the top of the equipment of molecular distillation, the product is resulted from steam condensation in contact with cooled walls, which is called as distillation. The stream that does not evaporate is called residue. As a separation technique used in the purification of low vapor pressure, high molecular weights or thermo labile liquid compounds[11-13], the molecular distillation operation is a complex process, which is characterized by space-varying and nonlinear dynamic behaviors. It could be represented by partial differential equations with solutions,

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leading to restrictions and difficulties in the development of control approach. However, the balance for high and safe operational performance together with the need to achieve the desired products requires the plant to be operated under control. Thus, molecular distillation models should be developed for easy to use, quick at calculating and robust enough to capture the main system.

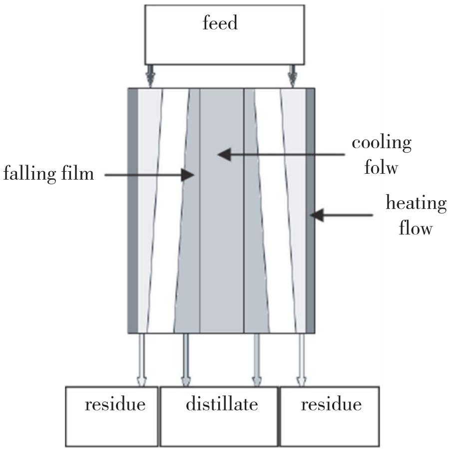

Fig. 1　Phase distribution scheme of a falling film molecular distiller

One of the most widespread controllers in chemical process is a proportional-integral-derivative (PID) controller system due to its simplicity, clear functionality and ease of implementation. To achieve the best levels of control, it is important to tune parameters k_P, k_I and k_D of PID controllers. However, conventional PID controllers must set initial parameters in advance according to engineers' knowledge, which can be remained unchanged during the regulation with other problems such as overshoot, poor stability and long adjustment time. The variable universe fuzzy PID controller combining the conventional PID controller with the artificial intelligence in terms of variable universe fuzzy logic can be a practicable solution[14-16]. This methodology considers both quantitative and qualitative information for guiding the mathematical formulations to adjust the most important process features[17-18]. This approach represents the process on the overall operating domain and with different types of data, which has the great advantage of not requiring system fundamental knowledge, instead of only input-output data, which makes it widely applicable in complex processes[19].

Among the parameters of molecular distillation plants, the vacuum degree is a very important operating parameter. How to control the vacuum degree in a reasonable value is the key to ensure standard process of molecular distillation and high product quality. Many researchers have discussed the benefits and importance of such methodology in process modeling. Alexandridis et al.[20] proposed a method based on fuzzy systems to solve the problem of nonlinear system identification. Gao et al.[21] used the self-adapting fuzzy-PID control to approximate real continuous functions with a selected accuracy using Takagi-Sugeno's fuzzy models for the real-time identification of nonlinear systems and to solve the nonlinear system control problem in the hydraulic servo control system. Micov et al.[22] developed a nonlinear, dynamic, fuzzy mathematical model for factors of the wiped film molecular distillation. Wu et al.[23] introduced a central response surface method combined with thin film evaporation and rectification coupling technology to study the relation of temperature, pressure and the reflux ratio to the yield and purity. Cerrada et al.[24] completed an approach for dynamical adaptive fuzzy modeling, which allowed the incorporation of the temporal behavior of the system variables into the fuzzy membership functions.

The objective of this work was to propose a variable universe fuzzy PID control method to improve optimization efficiency and investigate vacuum regulation for molecular distillation schisandra oil. A mathematic model of vacuum degree was assumed to be an adequate representation of the analyzed system. By introducing the contraction and expansion factor of variable universe, both fuzzy universes and parameters of PID controller were on-line tuned, which improved the performance of controller. Finally, numerical simulation results showed the effectiveness of the proposed method.

1　Modelling and methods

1.1　The mathematical model of the vacuum degree

The system based on the internal pressure of molecular distillation evaporator is a typical industrial process with large time delay and self-balance. The vacuum degree model of molecular distillation in this paper is approximately expressed by the second-order link with time delay T, which is expressed as the following expression.

$$G = \frac{K}{(T_1 s + 1)(T_2 s + 1)} e^{-\tau s} \tag{1}$$

$Y(s)$ and $Y(0)$ are the response values and initial values of molecular distillation vacuum system respectively. The relationship among G, $Y(s)$ and $Y(0)$ has the following relations.

$$Y(s) = Gu(s) + Y(0) \tag{2}$$

Steady state output of the system can be obtained by setting the amplitude of $u(s)$ to the step signal of U_1.

$$Y(\infty) = K_1 U_1 + Y(0) \tag{3}$$

The coefficient K is obtained as follows.

$$K = \frac{Y(\infty) - Y(0)}{U_1} \tag{4}$$

So setting $Y^*(s) = \dfrac{Y(s) - Y(0)}{Y(\infty) - Y(0)}$ can be launched as,

$$Y^*(s) = \frac{1}{s(T_1 s + 1)(T_2 s + 1)} e^{-\tau s}. \tag{5}$$

1.2 Experimental parameters

The experiment was carried out under the initial conditions that the heater terminal voltage was zero and opening degree of vacuum valve was zero. The temperature was kept with 105 ℃, and the initial pressure was set at 1 000 kPa. Then the step signal of the valve opening with amplitude of 270 degrees was given. By recording the data of pressure change, the sampling time was set with 10 min and sampling period as 5 s. Without considering the hysteresis, the system transfer function of the relationship between valve opening and evaporator vacuum degree can be approximately calculated as follows:

$$G(s) = \frac{839.98}{(40s + 1)(47s + 1)} e^{-10s}. \tag{6}$$

1.3 Variable domain

According to the idea of variable universe, the size of input and output universe can be changed and scaled according to relevant criteria and the requirements of control, and the intervals defined can also be divided by the fuzzy criteria. If the error e was fuzzed to the domain of $[-E, E]$, then $a(x)$ was called the expansion factor of the universe. The $a(x)$ can be expressed by various forms of functions. The magnitude of the expansion factor would determine the expansion level of action scope. Three different transformations of the domain are shown in Fig. 2. When scaling factor is greater than 1, the theoretical domain expands as shown in the upper of Fig. 2. On the other hand, when the scaling factor is less than 1, the theoretical domain shrinks as shown in the lower part of Fig. 2. The sign of fuzzy variables as NB, NM, NS, ZE, PS, PM and PB means negative big, negative medium, negative small, almost zero, positive small, positive medium and positive big.

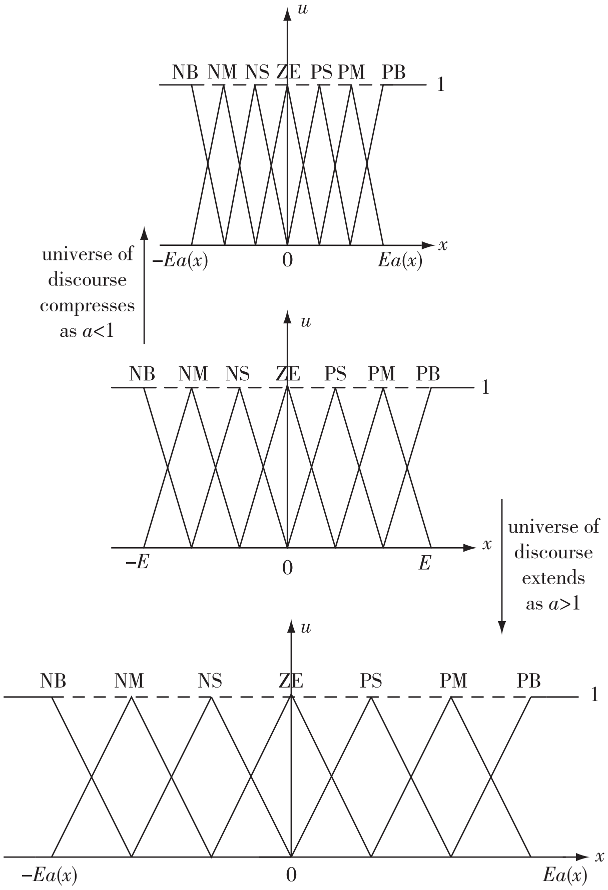

Fig. 2 The universe of discourse compresses and extends

1.4 Selection of scaling factor

The selection idea of scaling factor was as follows: for the case of double input, when the error charge rate (e_c) and error (e) of input were large, the domain remained unchanged. When the input was small then the fuzzy division of the domain was compressed correspondingly. Thus, the fuzzy division could be divided more finely when the input was small, and the contradiction between the control precision and fuzzy rules was solved, especially on the premise of system stability. Therefore, the control precision was higher. The scaling factor corresponding to the error rate and error passing through the fuzzy rules were a_1 and a_2. The definition of the fuzzy rules is shown in Table 1(where the extent of expansion or reduction is indicated respectively).

Table 1　Errors and fuzzy rules corresponding to error change rate and input scaling factor

e_c/e	PB	PM	PS	ZE	NS	NM	NB
a_1/a_2	B	M	S	Z	S	S	N

Similarly, the scaling factor b of the output universe of discourse can also be determined according to the size of e and e_c. Considering the following situation, when both e and e_c were very large and the positive and negative were the same, corresponding fuzzy rules were recorded as NB or PB, respectively, indicating that the difference between the expected value and the actual value of the system was very large, and the error tended to become larger. Therefore, the universe should be enlarged, and the error of the regulating system should be reduced using larger control quantity, which was recorded as VB. By analogy, its definition of fuzzy rules is shown in Table 2(where VB, MB, B, SB, S, V, S, and Z all indicate the extent of expansion or reduction).

Table 2　Fuzzy rules for output scaling factor *b*

e/e_c	NB	NM	NS	ZE	PS	PM	PB
NB	VB	VB	VB	S	VS	VS	Z
NM	VB	VB	MB	MB	S	S	S
NS	VB	MB	B	B	VS	MB	SB
ZE	B	B	VB	VB	VB	B	B
PS	S	B	VS	VS	B	B	VB
PM	SB	S	S	S	MB	B	VB
PB	Z	VS	S	VS	VB	VB	VB

2　Molecular distillation vacuum degree control system

For the vacuum control system of the molecular distillation, M files were compiled in Matlab environment. The design structure of the vacuum control system of the molecular distillation based on variable universe fuzzy PID is shown in Fig. 3. The system consisted of five modules, i.e., the adjustment of fuzzy expansion factor, the adjustment of variable universe fuzzy, the PID controller and the vacuum regulator of the molecular distillation. Firstly, the error and error rate were obtained by the differences between the output values and the expected values of the system. The expansion factors a_1, a_2, b of three domains were outputted using e and e_c as the inputs of the fuzzy system to determine the magnitude of the expansion factor. The adjustment values k_P, k_I, k_D of three PIDs were outputted using e_c, a_1, a_2, b as the inputs of the variable universe fuzzy system; and k_P, k_I, k_D, e, e_c as the inputs of the PID controller. The output was acted on the vacuum regulator of the molecular distillation to control its vacuum degree effectively.

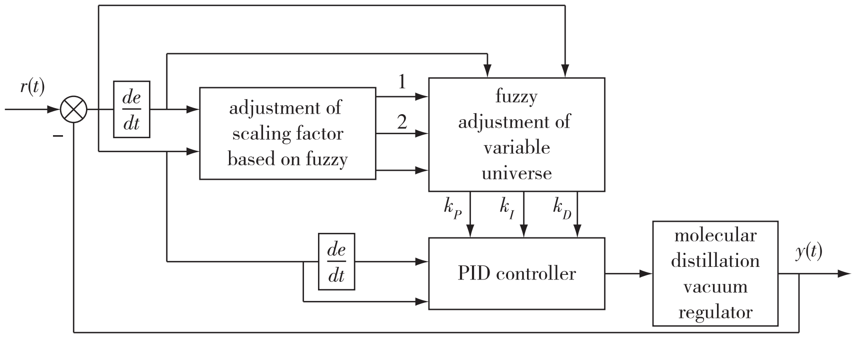

Fig. 3　Design structure of molecular distillation vacuum control system based on variable universe fuzzy PID

3　Results and discussion

The control range of molecular distillation vacuum degree can be kept between 0.5 and 5 Pa generally. Here the expected vacuum was set as 0.5 Pa. The range of error e was (−6, 6) and the range of error change rate e_c was(−5, 5). The error e and error change rate e_c were fuzzed to the domain of {−5,−4,−3,−2,−1,0,1,2,3,4,5} and k_P, k_I, k_D were fuzzed to the domain of {−0.05,−0.04,−0.03,⋯,0.03,0.04,0.05}. The dynamic response curve of vacuum setting at 0.5 Pa is shown in Fig. 4. The simulation results showed that the conventional PID controller had a fast-rising time, but overshoot was very large, counting an error of about 14%. The variable domain fuzzy PID had a slightly slow rise time, but the overshoot was very small, counting an error of about 3%.

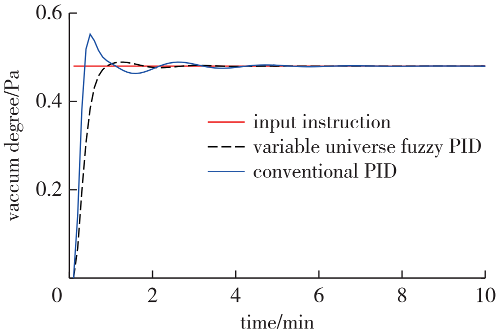

Fig. 4 Response curve of traditional PID and variable universe fuzzy PID control

The graph of the error between the output values of variable universe fuzzy PID control and the required vacuum values and its change rate when the vacuum degree was set at 0.5 Pa is shown in Fig. 5. The simulation results showed that in the control process, the improved PID error and error rate could converge to 0 in about 2 minutes.

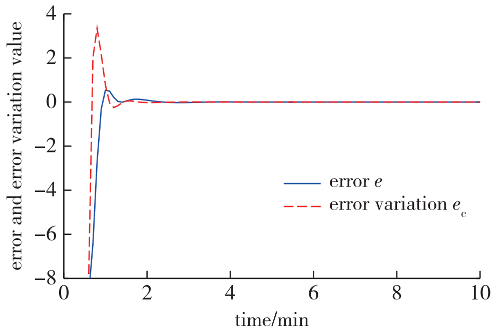

Fig. 5 Variable universe fuzzy PID error and its change rate curve

The adjusting curve of parameters in variable universe fuzzy PID with a vacuum setting at 0.5 Pa is shown in Fig. 6. The simulation results showed that the variable universe fuzzy PID could converge to the ideal value quickly and steadily in the process of parameter adjustment, which took about 0.6 minutes. In summary, the application of variable universe fuzzy PID in molecular distillation vacuum control was slower than the traditional PID control, but it had stronger stability and higher accuracy.

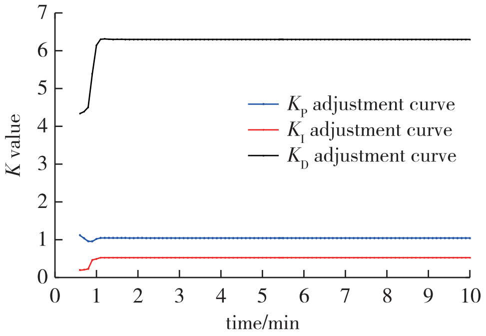

Fig. 6 Variable universe fuzzy PID parametric adjustment curve

The improvements can enhance the quality and yield of the product, namely, *Schisandra* oil, which is exactly the industrial production required. The results of comparisons between conventional PID control and variable universe fuzzy PID control is shows in Table 3. In Table 3,the initial *Schisandra* oil concentration was found to be 73.13% at 110 ℃ with the traditional PID method. When the proposed variable universal fuzzy PID method was applied, the distillate yield was increased with the increasing vacuum degree. The highest concentration was 83.78% at 110 ℃, which corresponded to a distillate yield of 75.2%.

Table 3 Comparisons between conventional PID control and variable universe fuzzy PID control

control method	temperature/ ℃	feed rate/ $(\mathrm{L \cdot h^{-1}})$	wiped film speed/ $(\mathrm{r \cdot min^{-1}})$	vaccum degree/Pa	concentration/ %	yield/ %
conventional PID control method	99	42	285	0.50	71.22	69.4
	104	42	285	0.55	74.51	70.4
	107	42	285	0.60	74.24	69.3
	110	42	285	0.65	73.13	70.2
variable universe fuzzy PID method	99	42	285	0.50	83.32	72.2
	104	42	285	0.55	82.92	74.3
	107	42	285	0.60	83.61	74.8
	110	42	285	0.65	83.78	75.2

4 Conclusions

The problem of vacuum degree regulating for molecular distillation was investigated in this study. Firstly, the mathematical model of vacuum degree was established. Then, the expansion factor was adjusted using the fuzzy rules, and the parameters of the PID controller were adjusted according to the output of the fuzzy controller. Finally, based on the simulation results of Matlab, it was concluded that the response time of the variable domain fuzzy PID was slightly slower than that of the traditional PID. However, the PID overshoot was much smaller than that of the traditional PID, and the adjustment time was much shorter and more stable, which was very suitable for the molecular distillation in the industrial control.

The analysis of results demonstrated that the fuzzy models represented the system in a very satisfactory way for the five output variables. In fact, the use of functional fuzzy models can represent a good alternative for modeling molecular distillation of *Schisandra* oil. The main advantage of the model approach was the use of an input/output data set together with qualitative information. As described previously, the analyzed system was usually complex, being represented by partial differential equations, which were particularly hard to be solved. On the other hand, the fuzzy model was simpler to be constructed, identified, and solved, and therefore it is an efficient way to model a system for process control and real-time optimization purposes.

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（责任编辑　梁辉）

基于变论域模糊 PID 算法的提高分子蒸馏五味子油质量和产量的真空度控制研究

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摘　要：采用超临界萃取五味子粗油作为实验原料，在多级分布式分子蒸馏装置中进行五味子精油的提纯实验，对分子蒸馏实验的工艺参数与产品指标之间的关系进行了讨论，并以分子蒸馏的真空度控制作为研究对象，建立了分子蒸馏真空度的数学模型。由于分子蒸馏控制系统具有非线性、纯滞后、时变的特点，针对传统 PID 控制及模糊 PID 控制难以很好地满足控制要求的缺点，本研究提出了利用变论域模糊 PID 算法实现分子蒸馏真空度的定值控制，通过引入变论域的收缩和膨胀因子，对模糊阈值和 PID 控制器的参数进行了在线调整，对模糊控制器的量化因子和比例因子进行了动态调整，从而提高了控制精度。在 Matlab 环境下与 PID 控制方法进行了仿真对比，结果表明变论域模糊 PID 控制方法具有更好的稳定性和自适应能力，该控制方法可以有效提高五味子精油的质量和产量。

关键词：变论域模糊 PID；参数优化；分子蒸馏；真空度控制；五味子油

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