STUDY ON THE SOFT-SENSOR AND CONTROL SCHEME FOR AN INDUSTRIAL AZEOTROPIC DISTILLATION COLUMN*

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Abstract: In this paper, control problems of an industrial Azeotropic distillation column were discussed and improved. At first, the soft-sensor of water content in the bottom of the column was built based on on-the-spot data collected by distributed control system (for short, DCS), through applying soft-sensor technology of regression, and a self-correcting module was also designed. The functions of estimation, display and correction about water content were realized on the DCS. At the same time, according to the actual quality control targets, an inferential control scheme based on soft-sensor was designed, in which the on-line estimating values of soft-instrument were used. The close-loop control of the product quality was realized in the scheme. As a result of increasing of Boolean calculation with constrained condition in the inferential control arithmetic, the reliability and practicability of the control system is strengthened. Application of the control system to the column showed that the control system can resolve effectively the problems that the product quality cannot be measured on-line and be close-loop controlled directly, and has realized the bounder control of water content in the bottom of the column.

Keywords: azeotropic distillation, regression and analysis, soft sensor, inferential control

1. INTRODUCTION

Distillation is the most important unit operation for separation processes commonly adopted in petroleum refinery and chemical industry. Because of the difficult factors, such as nonlinear, multi-variables, hard to measure quality factors online, the automatic control problem for distillation process has always been one of the hot subjects of automation researches. Many articles on distillation column controlling have been issued (Kumar, *et al*., 1999; Monroy *et al*., 1999). From the industrial facts, there exist the distillation columns with control problem (Ming Rao, *et a*l., 2002), which are seldom able to guarantee the products' purity mostly accounting for their overly simple control systems (I-Lung Chien, *et al*., 2000). Therefore, the excess purification is usually adopted in practice operation, which increased energy consumptions as well as decreased the product yield.

Recently, DCS is often introduced to control industrial equipment, especially in larger petrol-chemical plant. A contradict phenomenon arose in those petrol-chemical enterprises. In this paper, An advance control system based on DCS was proposed and designed, which has mainly relies on the present functions of DCS and improved the control of an industry distillation column.

2. PROCESS INTRODUCTION

The main subject of this article is focused on the workshop of butadiene-producing equipment, which existed almost all of the petrochemical enterprise.

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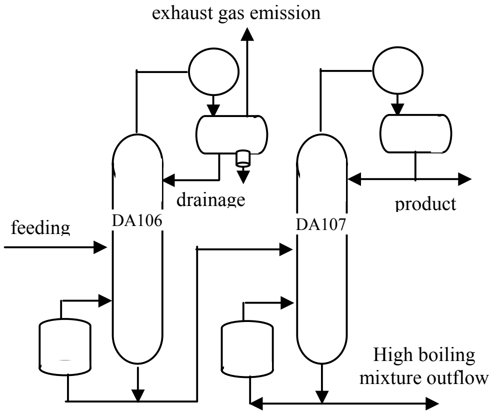

Fig.1 the flow sheet of butadiene distillation workshop section

Butadiene is the major monomer and raw material for producing styrene butadiene rubber, cis-1.4-polybutadiene rubber, nitrile rubber, ABS rosin and nylon. The distillation workshop section of butadiene produce equipments includes two distillation columns, Column DA106 and Column DA107, whose tasks are to remove the high-boiling-point impurities, such as cis-butene-2, butadiene-1, 2, ethyl acetylene and C_5, as well as low-boiling-point impurities such as methyl acetylene and water, and to achieve the final product, butadiene-1, 3. There are some control problems in the two distillation columns. Column DA107 is the production column. On the purpose of enhancing the operating and controlling level in the producing procedure, meeting the requirements of social economy, the former conventional control system has been changed into DCS system. Therefore, a set of control scheme need be improved accordingly. The improved scheme of Column DA107 has been reported in (Shi Zhang, *et al.,* 2002). In this paper, the control problem of water content about Column DA106 will be discussed.

The basic producing flow sheet of distillation workshop of butadiene-producing equipments is showed in the Fig.1.
Though most of the impurity has been dropped out from the raw material C_4 in the previous extraction distillation workshop, some impurities whose volatilities are close to butadiene-1,3 still exist. These impurities are to be dropped out in the columns of DA106 and DA107.
Column DA106 is an azeotropic distillation column with the main task of dropping out methyl acetylene, water and other lighter components. Methyl acetylene and other lighter components rise into the top of Column DA106 because of their low boiling point. Then they will be cut out with part of butadiene-1, 3, as the tail-gas into torch. The saturated water in feeding, as the azeotropic matter of butadiene-1, 3, is also taken to the top of the column. It is delaminated with butadiene in the circumfluence jar after condensation, and then is drained out from the bottom of the jar.

Water content in feeding is about 500(mg/kg), but in the products' purity index, the water content should not be over 20(mg/kg). The task of Column DA107 is to take off high-boiling mixture, namely, all the water in the bottom of Column DA106 will be carried into products, besides, through the experience of operators, if the water content is well controlled, the methyl acetylene consistency index is able to be guaranteed. As a result, the water content is a vital controlling target.

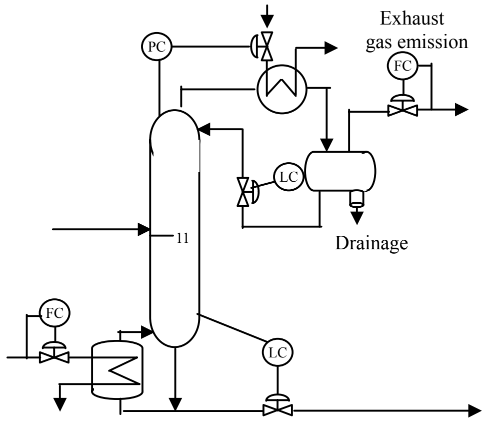

Fig.2 the flow chart with reference point of column DA106

The Figure 2 indicates the former controlling scheme of Column DA106. From the figure, it can be seen that this scheme is formed by all simple loops, without any quality-controlling loop. What's more, the current producing load goes far beyond the system's designing ability. Therefore, the former controlling scheme is hardly to fulfil the controlling task. In this case, the operators usually turn to the controlling method of increasing heat supply of the reboiler. The method pledges that the water content keeps not more than 20(mg/kg); however, it increases energy consumption. In addition, the water content in the production is also not stable.

In view of this case, the inferential control based on soft-sensor is designed instead of the former fixed value control system of the reboiler's heat supply, which can realize the direct quality control of water content. The key problem of the work is to solve the soft-sensor of water content.

3. THE SOFT-SENSOR OF WATER CONTENT

In recent years, it is widely reported that the soft-sensor technique has been introduced into the component estimation (Jingshou Yu, Ailun Liu, Kejin Zhang, 2000). Lots soft-sensor instruments in the form of commercial software have been released and utilised in practice production. Nevertheless, these softwares are so expensive that they were rarely introduced by the domestic enterprises. Soft sensor instrument, also soft sensor model, is the nuclear problem of the soft sensor technique. In the several modelling method, artificial neural network and regression analysis methods are often adopted. Because of the condition in factory, regression analysis method was selected to build the soft sensor model.

3.1 Assistant variable Selecting and analysis data setting

In this work, the possible process variables related with water content which can be obtained with soft-sensor instruments are as follows: two temperatures (the reboiler heating temperature T500-25 and the bottom temperature T500-26), three fluxes (the reboiler heating flux F133, the feeding F122, and the circulatory flux F134), one pressure (the bottom pressure P116) and one liquid location (the bottom liquid location L119).

As for the seven variables shown above, T500-25、T500-26、F122、F134、P116 are chose as process assistant variables. With the action of fixed value controlling loop, F133 and L119 are kept stable and remain fixed. And which have little to do with the change of water content, so the both variables are omitted. According to the result of the regressing analysis method, the five parameters above-mentioned are obviously connected with the water content, while F133 and L119 give no effect on water content. Lots of high frequency noises existing in measured value of the flux, which may influence the modelling work, so the measured value of F122 and F134 must be filtered at first, and then to do regression analysis.

Another difficult problem is that there is no practical value of the water content at the bottom of the column DA106, only a test point located at the exit of column DA107 (product jar) for sampling and analysing water content every 8 hours. Consider that the water content in the product will not change a lot from the bottom of Column DA106 to the product jar, it can be supposed reasonably that water content in the product jar is only the express of water content in Column DA106 bottom after a period of delaying-time (τ). At the same time, some analysis values of water content in the column DA106 were added temporarily. And according to comparison of the both curves between these analysis values and those in the product jar, the same conclusion was made, also with the experiences of the operators, the value of τ is confirmed about 1 hour. As a result of the water content at the bottom of Column DA106 can be shown by the analysis value of the water content in the product, the analysis values of water content in the product jar were used as the estimated variable of the soft sensor model.

3.2 Building the soft-sensor model

The abundant on-the-spot data (420 groups), which were collected by distributed control system, were classified as the two parts: the modeling set (300 groups) and the verifying set (120 groups). A soft sensor model is built with regression and analysis technology based on the modeling set (300 points). The regression model can be shown as follows:

$$S_{130}(t) = \sum_{i=0}^{5} a_i \times x_i(t-\tau) \qquad (1)$$

Where:

$S_{130}(t)$: the estimated value of water content at t;
τ: Delaying-time;
$x_i(t-\tau)$ ($i = 1, 2, \cdots, 5$): 5 assistant variables;
a_i ($i = 0, 1, 2, \cdots, 5$):Regressing-coefficients.
The values are:

a_0	-84.677507
a_1	2.841364
a_2	-0.655388
a_3	-1.731556
a_4	1.582286
a_5	231.365314

The verifying set data are used to verify the model's extrapolative ability. The results of the model's simulation and extrapolation are shown in Fig.3.

In the Fig.3, the abscissa values show sampling numbers. It is obvious that the precision of the proposed model is very high, and the extrapolative ability can also satisfy the control request. Moreover, the model is simple in form and easy to realize in the project.

3.3 On-line correcting the soft-sensor model

Because of the influences from time varying, nonlinear and no integrality of modeling factor established in product process, the soft-sensor model has to be corrected on-line (Jingshou Yu, 2002). The correction work may classify into two types. One is long-time correction, that is, after the distillation process running for a period of time, a new model will be reconstructed and substituted the former model; the other is short-time correction, which is carried out on-line, it means that the short correction is to correct the model with the error between the analysis value every 8 hours and the calculating value of soft-sensor model. What requires our attention is that the time when the analysis data is sent to the control-room delays the sampling time

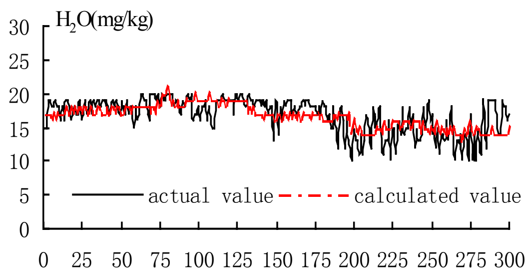

Fig.3(a) Training plot of the regression

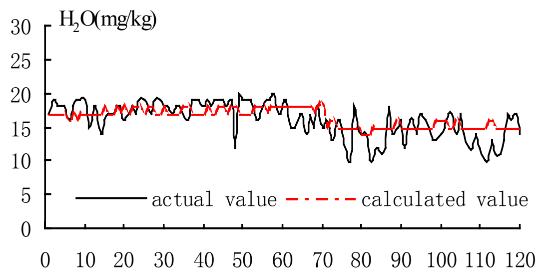

Fig.3(b) Verifying plot of the regression

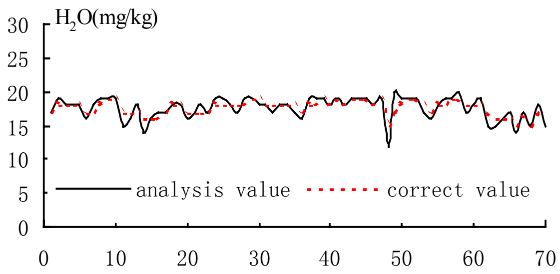

Fig.4 on-line corrected effect of soft-sensor model

about δ time, so the calculating value at the moment of sampling should be kept in order to compare the two groups of data at the same time. Correction formula is as follows:

$$\Delta S_{130}(t) = \alpha \times [S_{\alpha 130}(t-\delta) - S_{130}(t-\delta)] \qquad (2)$$

Where：

$\Delta S_{130}(t)$:The corrected value of the water content at t;

α: The corrected coefficient, here is 0.5;

δ: The analysis delay-time;

S_{a130} (t- δ): The analysis value of the water content at t- δ;

S_{130} (t- δ): The estimated value of the soft instrument at t- δ.

From the Fig.4, on the condition that the extrapolate ability of the soft-sensor mode is not very better (see the Fig.3), only through on-line correcting, the accuracy of the soft-sensor mode has be advanced so that the soft sensor model corrected on-line may be applied to the practice.

4、THE CONTROL SCHEME AND PRACTICAL APPLICATION

As shown above, the prime problem about the control system of column DA106 is that there are not direct or indirect quality control loops. So the operators adjusted the given value in control loop of reboiler heating flux by hand, only basing on sampling analysis data every 8 hours, to control the water content of the column bottom. Under this distillation operation condition, not only the water content in the product jar cannot be ensured availably, but also the energy consumption is increased greatly. Therefore, an inferential control scheme based on soft sensor is designed to substitute the former control loop of the water content in the column bottom.

4.1 Basic control scheme

There is a basic control scheme shown in following Fig.5.

In the figure, the soft-sensor instrument is just the soft-sensor model built above.

In view of the possibility of project realization, the water content controller only adopts PID arithmetic. So, except the soft-sensor model needs to program in Command language, all the control schemes are easily carried out by configuration in DCS.

On the DCS of the column, the control scheme was put in practice, and tried to run for a period of time. It is proved that the scheme is available. Firstly, the control effects of water content is so ideal that the value can be controlled between 18~20(mg/kg). Secondly, the heating of reboiler was decreased than before.

4.2 Constrained control in the control scheme

At the same time, when the work situation changed greatly, this control scheme could not run steadily for a long time. It is reason that along with the great change of the word situation, the great fluctuation of control variable occurred. Therefore, the condition of work might also leave the perfect balance condition.

Through analyzing the technique process, the reason caused this phenomenon was found. When control variables are changed greatly, the rising steam capacity within the column is influenced. In Figure 2, for the circulatory flux is the control variable of liquid level of reflux tank, the large change of the rising steam capacity quickly causes the circulatory flux fluctuates greatly. However, this fluctuation could not be allowed. According to the rule of should

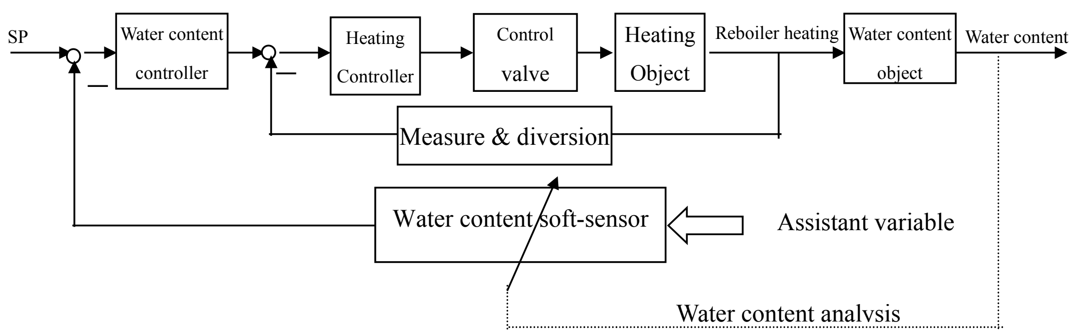

Fig5 water content inferential control system flow chart of DA106 column bottom

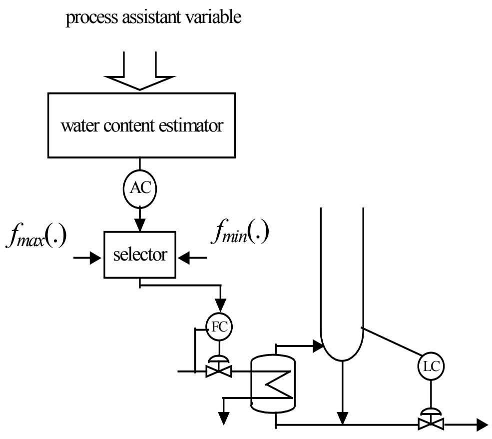

Fig.6 Improved inferential control scheme

control techniques, the circulatory flow in the column be limited between 1.3 to 1.7 times of feeding. For these reasons, a constrained control with the logic module is added to the above inferential control scheme. The inferential control scheme with constrained control is shown in the Fig.6.

The relation between input and output in the selector is:

$$out = \begin{cases} f_{\max}(.) & if \quad out_{AC} \geq f_{\max}(.) \\ out_{AC} & if \quad f_{\min}(.) \leq out_{AC} \leq f_{\max}(.) \\ f_{\min}(.) & if \quad out_{AC} \leq f_{\min}(.) \end{cases} \quad (3)$$

Where:
out: The output of selector;
out_{AC}: The output of water content's controller;
$f_{max}(.)$: The maximal heating;
$f_{min}(.)$: The minimal heating.
Here $f_{max}(.)$ and $f_{min}(.)$ are decided by following process:

(1) Through analyzing the technique process, the technique parameters are decided which are all related with heating of reboiler, including the feeding F122, the circulatory flow F134, the temperature of heater's input and output T133 and T500-25, the column bottom temperature T500-26 and pressure P116;
(2) The regress relation, *f* (F122, F134, T133, T500-25, T500-26, P116), was obtained by regression analysis with the field data;
(3) Supposing the circulatory flow is enhanced to

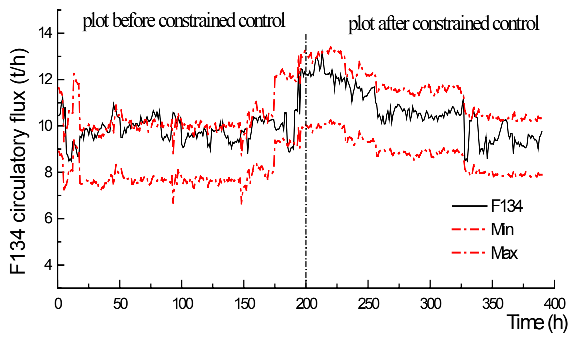

Fig.7 the effect of the comparison of before and after the constrained control

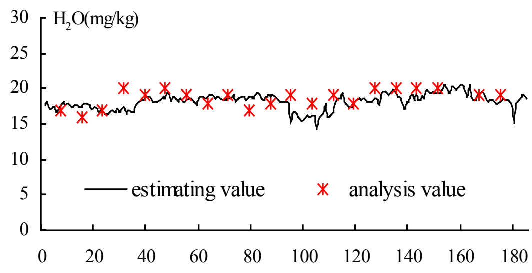

Fig.8 the practical effect of inferential

1.7 or 1.3 times separately, then the maximal heating and the minimal heating function *f* (.) are listed as follow:

$f_{max}(.)$= *f* (F122, 1.7×F134, T133, T500-25, T500-26, P116)
$f_{min}(.)$= *f* (F122, 1.3×F134, T133, T500-25, T500-26, P116)

After the constrained control of the circulatory flow was added to the inferential scheme, the circulatory ratio can be controlled effectively in the rational scope. So the phenomena of the bigger circulatory ratio could be avoided, that is the water content of the column bottom is too lower. The Fig.7 shows the result of the comparison effect that the constrained control has be applied to the worksites.

4.3 The practical application of control scheme

The control scheme has been applied preferably to the column DA106 for half of years. Figure 7 gives the real time control effect. In the Fig.7, it is shown that the fluctuation of water content in the product is on the small side after the control scheme has been applied to the column. It can be controlled within the17~20(mg/kg) scope, which justly meet the control goal that the water content in the product is less than 20(mg/kg). At the same time, the change of the circulatory flow also became relatively steady, and the energy consumption was decreased greatly.

5.CONCLUSIONS

In this paper, aiming at an industrial azeotropic distillation column, an inferential control scheme with constrained control was designed to substitute the former control scheme of column. And the bounder control of water content in the bottom of the column has been realized. Firstly, a soft-sensor model and an inferential control scheme based on the soft sensor model are build and designed. Then, according to the practical running, the constrained control is added to the scheme. As a result of Boolean calculation added to the control arithmetic, the robustness of the control system is strengthened. So the system could be able to adapt preferably great fluctuation of work situations. Through the several months of practical application, it proved that the control system is feasible and available to run steadily for long time.

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