Study on hardware-in-the-loop simulation of beer fermentation system

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Abstract: Beer fermentation process is a complex biochemical reaction process. It is the most important to control temperature of the wort in fermentation tank in accordance with the beer fermentation temperature curve so as to ensure the completion of fermentation. The controlled object is characterized by large inertia, long time delay and mutual coupling of three temperature areas. Based on this, a temperature control method for beer fermentation system is designed. Using digital incremental proportion integration differentiation (PID) control algorithm, the controlled quantity is transmitted to the controlled object after diagonal matrix decoupling. This simulation system can be completed in laboratory using VB and Kingview software, so it has the features of good security and low cost. It is very suitable for experimental teaching.

Key words: beer fermentation system; hardware-in-the-loop simulation; diagonal matrix decoupling; proportion integration differentiation (PID) control algorithm

CLD number: TP391.92 **Document code**: A
Article ID: 1674-8042(2014)01-0071-04 **doi**: 10.3969/j.issn.1674-8042.2014.01.015

In the past, workers used the traditional manual operation method to control beer fermentation process. This method has the characteristics of intensive labor, low productivity, more beer wine loss, low yield and poor quality[1]. Using computer to automatically control beer fermentation process can solve these problems, and the quality of the beer has also been greatly improved. In this article, we use VB program and Kingview software to simulate the beer fermentation process in laboratory, which also has great significance to experimental teaching.

1 Fermentation process

The main equipment of beer fermentation is beer fermentation tank. The cylindrical conical tank has become the mainstream in recent years gradually. The beer fermentation tank consists of outer layer and inner layers with insulation materials filled between the two layers. There are also three cooling areas between the two layers, which are connected with three valves. The controller adjusts the opening size of the valve to control the refrigerant's flow rate into the cooling area, and then controls the temperature in the tank to make it comply with the beer fermentation temperature curve. The schematic diagram of beer fermenation tank with three temperature areas and pipelines is shown in Fig. 1.

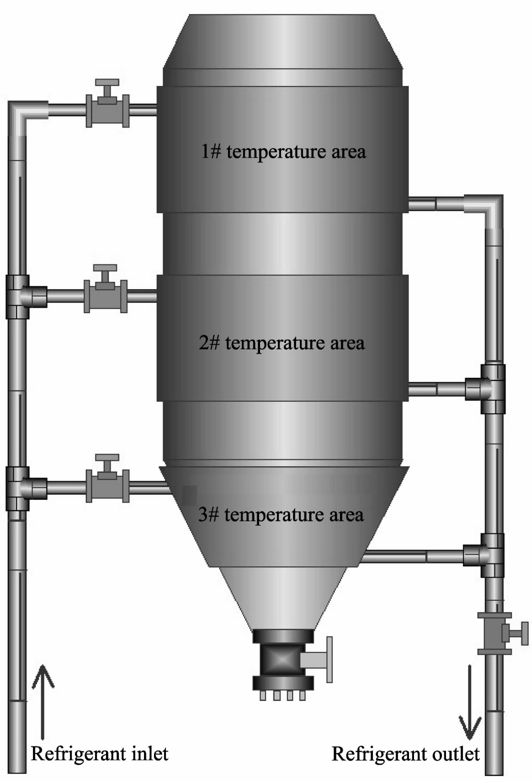

Fig. 1 Schematic diagram of beer fermentation tank with three temperature areas and pipelines

The control accuracy of fermentation temperature

※ **Received date**: 2013-11-02
Foundation item: Shandong Province Department of Education Science and Technology Program(No. J05C11)
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in the entire process determines success or failure of the beer fermentation. Therefore, the temperature must be strictly controlled in the whole fermentation cycle. The typical temperature control curve of fermentation process is shown in Fig.2.

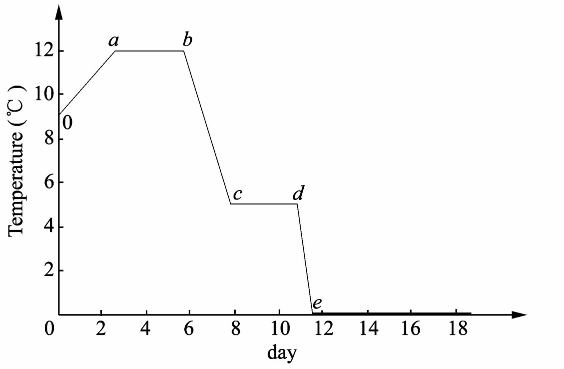

Fig.2 Typical temperature curve of fermentation process

2 Realization of the system

The principle diagram of beer fermentation control system is shown in Fig.3. $D(z)$ is pulse transfer function of the controller, $\boldsymbol{F}(z)$ is the transfer function of decoupling compensation matrix, $H(s)$ is the zero-order hold and $G(s)$ is the mathematical model of control object.

2.1 Mathematical model of controlled object

Based on practical experience and system identification, the author of Ref.[2] regarded one of temperature areas' mathematical models as a first-order inertial system with delay, which is defined as

$$G_{ij}(s)=\frac{K_{ij}}{1+T_{ij}s}\mathrm{e}^{-\tau_{ij}s}\quad(i,j=1,2,3),\tag{1}$$

where $G_{ij}(s)$ is the transfer function of valve j to temperature area i; T_{ij} is the inertial time constant; K_{ij} is the ratio of coefficient; and τ_{ij} is the delay time constant.

Transfer function of zero-order hold is

$$G_h(s)=\frac{1}{s}-\frac{e^{-T_s}}{s}=\frac{1-e^{-T_s}}{s},\tag{2}$$

According to Fig.2 and Eq.(1) and Eq.(2), it can be got as

$$\frac{y_{11}(s)}{U_{1p}(s)}=G_h(s)G_{11}(s)=\frac{1-e^{-Ts}}{s}\frac{K_{11}}{1+T_{11}s}e^{-\tau_{11}s}.\tag{3}$$

The differential equation can be obtained as[3]

$$y_{11}(k)=e^{-\frac{T}{T_{11}}}y_{11}(k-1)+K_{11}(1-e^{-\frac{T}{T_{11}}})U_{1p}\left(k-1-\frac{\tau_{11}}{T}\right).\tag{4}$$

Using the same method, other differential equations are obtained and then the total output equations are

$$\begin{cases}y_1(k)=y_{11}(k)+y_{12}(k)+y_{13}(k),\\ y_2(k)=y_{21}(k)+y_{22}(k)+y_{23}(k),\\ y_3(k)=y_{31}(k)+y_{32}(k)+y_{33}(k).\end{cases}\tag{5}$$

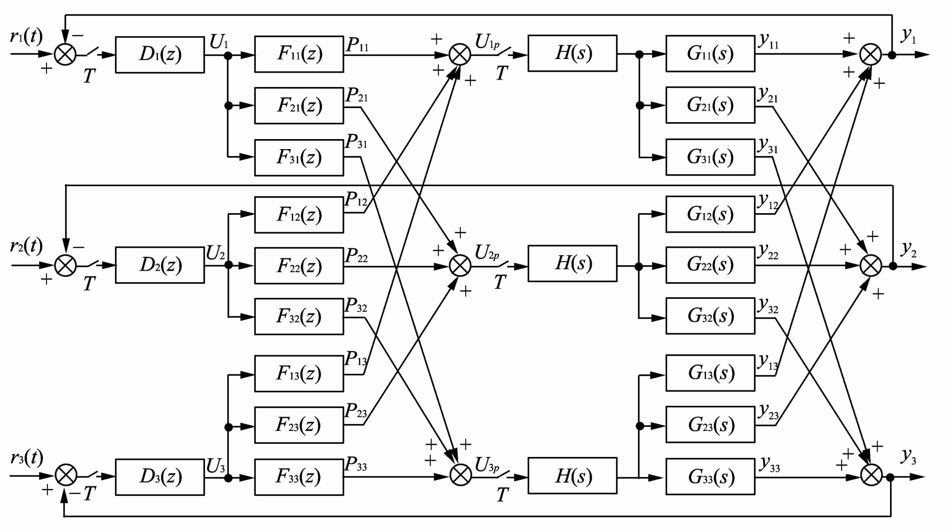

Fig.3 Principle diagram of beer fermentation control system

2.2 Decoupling control algorithm

Due to the mutual coupling between different temperature areas, the temperature of one area can not only be directly affected by its own control variable, but also indirectly influenced by the other two control variables[4]. Therefore, using control algorithm, output should be decoupled[5]. In this paper, diagonal matrix decoupling algorithm is used[6] based on the fact that the product of controlled object's characteristic matrix and decoupling matrix is a diagonal matrix as

$$\begin{bmatrix} G_{11}(z) & G_{12}(z) & G_{13}(z) \\ G_{21}(z) & G_{22}(z) & G_{23}(z) \\ G_{31}(z) & G_{32}(z) & G_{33}(z) \end{bmatrix} \begin{bmatrix} F_{11}(z) & F_{12}(z) & F_{13}(z) \\ F_{21}(z) & F_{22}(z) & F_{23}(z) \\ F_{31}(z) & F_{32}(z) & F_{33}(z) \end{bmatrix} = \begin{bmatrix} G_{11}(z) & 0 & 0 \\ 0 & G_{22}(z) & 0 \\ 0 & 0 & G_{33}(z) \end{bmatrix}. \quad (6)$$

According to Eq. (6), $\boldsymbol{F}(z)$ can be written and calculated as

$$\boldsymbol{F}(z) = \begin{bmatrix} G_{11}(z) & G_{12}(z) & G_{13}(z) \\ G_{21}(z) & G_{22}(z) & G_{23}(G) \\ G_{31}(z) & G_{32}(z) & G_{33}(G) \end{bmatrix}^{-1} \begin{bmatrix} G_{11}(z) & 0 & 0 \\ 0 & G_{22}(z) & 0 \\ 0 & 0 & G_{33}(z) \end{bmatrix}. \quad (7)$$

The calculation process is very cumbersome, so it can be completed by Matlab[7].

2.3 Temperature control algorithm

Temperature control algorithms for temperature areas 1,2 and 3 of virtual beer fermentation system are the same, where taking temperature area 1 as an example.

In this paper, digital incremental proportion integration differentiation (PID) control algorithm is used, and it is described as[1].

$$\Delta u_1(k) = q_0 e_1(k) + q_1 e_1(k-1) + q_2 e_1(k-2),$$
$$q_0 = \mathrm{K_P}\left(1 + \frac{T}{\mathrm{T_i}} + \frac{\mathrm{T_d}}{T}\right),$$
$$q_1 = -\mathrm{K_P}\left(1 + \frac{2\mathrm{T_d}}{T}\right),\ q_2 = \mathrm{K_P}\frac{\mathrm{T_d}}{T}, \quad (8)$$

where $\mathrm{K_P}$ is proportionality constant, $\mathrm{T_i}$ is integration time constant, $\mathrm{T_d}$ is differential time constant, $e_1(k)$ is temperature deviation value of current time, $e_1(k-1)$ is temperature deviation value of last sampling time and $e_1(k-2)$ is temperature deviation value of last two sampling times. The final output controlled variable at current time is

$$u_1(k) = u_1(k-1) + \Delta u_1(k). \quad (9)$$

$P_{11}(k)$ is got by putting Eq. (9) into $F_{11}(z)$; $P_{21}(k)$, $F_{21}(z)$; $P_{31}(k)$, $F_{31}(z)$. The others can be got using the same method. Finally, the total output equations are

$$\begin{cases} U_{1P}(k) = P_{11}(k) + P_{12}(k) + P_{13}(k), \\ U_{2P}(k) = P_{21}(k) + P_{22}(k) + P_{23}(k), \\ U_{3P}(k) = P_{31}(k) + P_{32}(k) + P_{33}(k). \end{cases} \quad (10)$$

3 Simulation result

The simulation program is completed by VB[8] with appropriate constants. The simulation results are displayed by Kingview software[9] via dynamic data exchange (DDE) connection, including animation interface, real-time temperature curve and historical temperature curve.

Fig. 4 is the historical temperature curve. It can be seen that the error of temperature curve is within the allowance, so the basic requirements of the system are met.

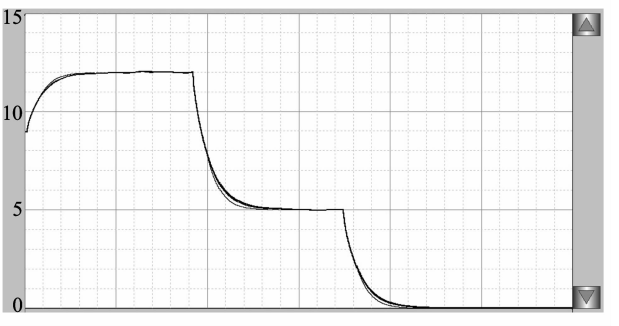

Fig. 4 Historical temperature curve

4 Conclusion

In this paper, a temperature control method for beer fermentation system is presented. Based on digital incremental PID control algorithm which controls transmission quantity to controlled object after diagonal matrix decoupling. The simulation system is completed by VB and Kingview software. The simulation results show that the in the laboratory. So it has the features of good security and low cost, and is very suitable for experimental teaching.

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啤酒发酵系统的半实物仿真研究

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摘　要： 啤酒发酵过程是一个复杂的生化反应过程，控制目标是控制发酵罐内麦汁的温度符合发酵温度曲线，保证发酵的顺利完成。针对控制对象大惯性、大时滞及3个温区相互耦合的特点，我们采用数字增量式PID控制算法实现控制，控制量经过对角阵解耦后作用到控制对象。最后，啤酒发酵系统由VB程序和组态王软件仿真。该系统可以在实验室中完成的，具有安全性高、成本低的特点，非常适用于实验教学。

关键词： 啤酒发酵系统；半实物仿真；对角阵解耦；PID控制算法

引用格式： YAO Chao-xiu, ZHENG Juan-juan, JIANG Yu-long, et al. Study on hardware-in-the-loop simulation of beer fermentation system. Journal of Measurement Science and Instrumentation, 2014, 5(1): 71-74. [doi: 10.3969/j.issn.1674-8042.2014.01.015]