Simulation of an improved PID algorithm and its application in thermal conductivity measuring apparatus

Jun Wang¹, Yongbin Wei¹, Wenjie Chen¹

Technical Center, China State Construction Engineering Corporation Limited, No. 15 of Linhe Street, Shunyi District, Beijing 101300, People’s Republic of China
Corresponding author’s e-mail: 5129625@qq.com.

Abstract. The working principle of an improved PID algorithm and its application in thermal conductivity measuring apparatus is presented in this work. A special simulation application software was developed for parameter tuning and optimizing. The simulation result was used in the thermal conductivity measuring apparatus which is designed under the principle of guarded hot plate. Therefore, the testing process time required for the thermal conductivity of building thermal insulation material was cut by one-third, from one hour to twenty minutes.

1. Introduction
The building energy conservation is a new issue which needs as much study as possible recently [1]. How to reduce building energy consumption has become a subject for the construction industry to solve [2]. Among varied methods, the application of external insulation materials is the most direct way. Thermal conductivity is one of the most important performance parameters, therefore, the testing apparatus of it has been extensively studied. Various control structures have been proposed for the temperature control system, however, among these controllers the proportional plus integral plus derivative (PID) was the most preferable controller. The PID controller is distinguished by its robust performance over a wide range of operating conditions and simplicity of structure design [3]. In the field of automatic control field, PID parameter tuning and optimizing is an important issue and it needs experienced engineers to do the job [4]. Therefore, over the past few decades researchers have sought to investigate how to get a better result of the PID parameter.

In this paper, we present an improved PID algorithm for temperature controlling system and it is applied to the thermal conductivity measuring apparatus. For getting the PID parameter tuning rapidly and accurate, a simulation application software is developed.

2. Method of control algorithm and simulation

2.1 Discretization of the parameters
PID classic formula is equation (1). e is respectively the deviation, r[t] is input and c[t] is output of the controller. First of all, the continuous time parameter “t” is replaced by a series of sampling time point “kT” (k=1, 2, 3……; T is a unit time). Equation (1) is changed into equation(2). The incremental control algorithm of discrete PID control rule is equation (3). In which, \( k_i \) is respectively the integral coefficient, \( k_d \) is differential coefficient, T is sample period, \( k_p \) is proportional coefficient, \( T_i \) is integral time constant, \( T_d \) is differential time constant. k is respectively the sample order number, u[k]
is output value of controller, $e[k]$ is deviation value of system at sample time $k$, as well as deviation value of system at sample time $k-1$ and $k-2$ [5].

$$u = k_p (e + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de}{dt}) \quad (e = r[f] - c[f]) \quad (1)$$

$$u[k] = k_p \{ e[k] + \frac{T}{T_i} \sum_{j=0}^{k} e[j] + \frac{T_d}{T} (e[k] - e[k-1]) \} \quad (2)$$

$$\Delta u[k] = u[k] - u[k-1] = k_p \{ e[k] - e[k-1] \} + k_i e[t] + k_d \{ e[k] - 2 \cdot e[k-1] + e[k-2] \} \quad (3)$$

$$k_i = \frac{k_p T}{T_i}, \quad k_d = \frac{k_p T_d}{T} \quad (4)$$

2.2 Algorithm of the simulation software

The structure of temperature control system is shown in figure 1. There is a comparator to deal with the absolute value of the difference between setting value “$r$” and actual value “$c$”. Under the limit of rated voltage of programmable direct-current power, the maximum voltage is set to 30 volt. If the temperature difference between setting value and actual value is less than 5 degrees Celsius, the PID controller will be utilized. Otherwise, the output voltage of the power supply will be set to the maximum value. The electric heating wire is heated to generate heat, and ultimately maintains the temperature at a setting value. The relationship between deviation of temperature and output voltage of programmable power is deduced by electric power equation (5) and special heat equation (6).

![Figure 1. PID system block diagram.](image)

$$Q = \frac{U(t)^2}{R} t = Cm \cdot \Delta t \quad (5)$$

$$\Delta t = e = \frac{U(t)^2}{RCm} \quad (6)$$

2.3 Result of the simulation software

The interface of simulation program is shown in figure 2. A response curve is plotted according to the coefficient that the operator input. Several curves could be shown at the same time and these curves are distinguished by different color, as shown in the figure 3.
First of all, the integral coefficient $K_i$ remain unchanged, and it is set as 1, meanwhile the proportional coefficient $k_p$ is increased gradually. As shown in figure 4, the curve of "$k_p = 40$" is smooth, therefore the proportional coefficient is set as 40. Then the $k_p$ remain unchanged, the $k_p$ is reduced gradually. As shown in figure 5, the curve of "$k_i = 0.01$" is better.
3. Apparatus design and application

3.1 Structure of the apparatus
The apparatus is designed under the principle of guarded hot plate which is shown in figure 6. [6]Under stable conditions, the one-dimension heat flux is established between two sides of parallel plates, which mean that one side of temperature is different from the other one. The apparatus can maintain the upside surface of test specimen at a higher temperature and the downside surface of test specimen at a lower temperature, such as the upside is 35 degrees Celsius and the downside is 25 degrees Celsius. Therefore there is a constant difference in temperature between upside and downside surface of the test specimen “E”. There is a constant heat flux through the test specimen. According to the thermal conductivity equation (7), the thermal conductivity can be calculated. The test apparatus is mainly made of aluminum, with dimension of 35cm × 35cm × 50cm, the digital model of apparatus is shown in figure 7 and the real picture of apparatus is shown in figure 8. To prevent heat exchange between the chamber atmosphere and the power measurement and heating unit, besides the thermal insulation heating unit, the rubber-plastic insulation material is selected to insulate the outer surface of power measurement and heating unit due to its low thermal conductivity.

Figure 6. The working principle of guarded hot plate.
A. thermal insulation heating unit; B. power measurement and heating unit (high temperature);
C. temperature sensor; D. thermal-insulating layer;
E. test specimen; F. heating unit (low temperature) ;
\[ \phi = -\lambda A \frac{\Delta t}{\delta} \]  

(7)

3.2 Application of the apparatus

The application software was developed to measure the power and the temperature between upside and downside surface of the test specimen. All of the data were stored as a text file on the control computer at the same time. The real-time calculation process of the thermal conductivity can be shown on the interface of the software, as shown in figure 9. The figure of curves which indicated the Real-time temperature of different parts was updated in ten minutes. To justify the validity of this apparatus, a standard specimen was used as test one. The thermal conductivity of the reference specimen is 0.0332, the result that was calculated by the test apparatus is 0.0366.

4. Conclusion

The apparatus developed in this work was shown that adopting improved PID control algorithm is able to own obvious advantage in robustness and steady control precision. The testing time is shortened under the premise of keeping the accuracy of the result.

Acknowledgments

This work was carried out under the project with funding from the China State Construction Engineering Corporation, China. Authors wishing to acknowledge financial support from CSCEC-2019-Z-5.
References

[1] Huang Wei, Wu Qian. (2013) Fuzzy- PID Controller of Parameter Based Auto-tuning and Its Application. J. Hydromechatronics Engineering, Vol.41 No.6:81-86.

[2] Zhongnan Song, Yunxing Shi, and Weidong Zhang. (2012) Development of a continuous testing apparatus for temperature reduction performance of cool coatings. J. Review of Scientific Instruments., 83:054901.

[3] Mouayad A. Sahib., Lupton, R.A. (2015) A novel optimal PID plus second order derivative controller for AVR system. J. Engineering Science and Technology. International Journal 18: 194-206.

[4] Jiafei Zhao, Bin Wang. (2015) A novel apparatus for in situ measurement of thermal conductivity of hydratebearing sediments. J. Review of Scientific Instruments., 86:085110.

[5] Qinming Meng. (2003) The principle of automatic control. Higher Education Press, Beijing.

[6] (2008) GB/T 10294 Thermal insulation-Determination of steady-state thermal resistance and related properties-Guarded hot plate apparatus. China Standard Press, Beijing.

[7] L. Vozar. (1996) A computer-controlled apparatus for thermal conductivity measurement by the transient hot wire method. J. Journal of Thermal Analysis, Vol.46:495-505.

[8] T. Dasgupta and A. M. Umarji. (2005) Apparatus to measure high-temperature thermal conductivity and thermoelectric power of small specimens. J. Review of Scientific Instruments., 76:094901.