DISTURBANCE OBSERVER BASED THERMAL HYDRAULIC CONTROL OF THE LEAD BISMUTH EUTECTIC LOOP

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A disturbance observer based temperature control algorithm is proposed for the highly coupled thermal hydraulic system existing in the Target Circulation (TC-1) loop of the 1MW power acceleration-driven system (ADS). The TC-1 is the pilot molten lead-bismuth eutectic (LBE) target circulation loop that was designed to accommodate an 800 MeV proton beam power of 1MW. All the loop components are located inside a compact rectangular container and the loop is custom designed for the Los Alamos National Laboratory (LANL)'s LANSCE accelerator. Due to close proximity of each component in the loop, there is significant challenge in the precise temperature control of each zone. Especially, the electromagnetic pump used for molten lead circulation becomes a big heat source particularly due to its low efficiency. As for the safety consideration, all components in TC-1 have to be heated up at same level. It is difficult to test the individual heating zone using proposed algorithm. As a result, a single furnace was used to simulate the heater in TC-1. The disturbance observer based control methods have been reported to compensate modeling uncertainties as well as external disturbance. The disturbance observer regards the difference between the actual output and output of the nominal model as an equivalent disturbance applied to the nominal model. The proposed disturbance observer based control algorithm achieves a precise tracking of set temperatures despite of highly coupled thermal disturbance existing in the loop.

I. Introduction

Target circulation (TC-1) loop is the pilot molten lead-bismuth eutectic (LBE) target circulation loop that was designed to accommodate an 800 MeV proton beam power of 1MW. Nine heating components are located inside a compact container (see Fig. 1). As a part of the experimental installation being developed in LANL for testing in the proton beam of the LANSCE accelerator, TC-1 has two important test goals: the demonstration of serviceability of a molten lead-bismuth target as well as efficiency of its control and experimental investigation of neutron generation as well as effects accompanying the interaction of the proton beam and lead-bismuth.

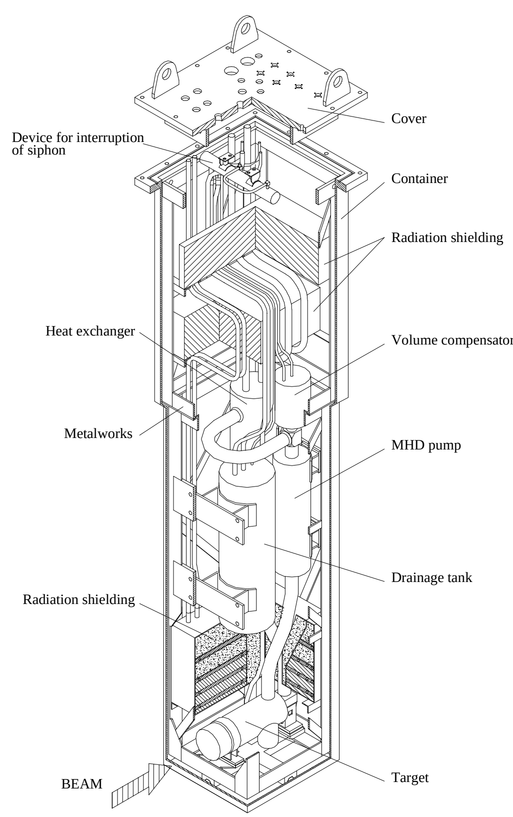

Fig. 1. TC-1 loop with nine heating zones.

Zone 1 is the upper part of drainage tank, zone 2 is the lower part of the drainage tank, zone 3 .1 is the upper part of heater exchanger; zone 3.2 is the lower part of heater exchanger, zone 4 is MHD pump and pipe with flower meter, zone 5 is volume compensator, zone 6 is the target itself and pipe nearby, zone 7 is inlet pipelines for pressurizing and fist coolant filling, zone 8 is siphon interruption device and pipeline nearby.

Due to its special design, the thermal control during the heating-up, melting, and working process shows difficulties due to close proximity of each component. In addition, all components should be heated up to the same level with same heating rate in order to reduce the thermal difference. The working temperature is 200ºC [1].

The traditional band heating control scheme was used to maintain the temperature within a narrow bank, say between 190 and 200 ºC. The control scheme was also constrained with the conditions of heating rate and the allowable temperature difference between different zones. The heating process was slow and final temperature show significant fluctuations beyond the setting temperature bank. This old algorithm also shows its weak ability to reject the external disturbance, such as the interferences from near heaters, cool cover gas flow and Electro-magnetic pump.

The common thermal processes are widely used in industry where they are usually discontinuously controlled by ON/OFF or ON-Half-OFF controllers [2]. The heaters in TC-1 are controlled by solid-state relay using ON/OFF scheme.

More than half of the industrial controllers in use today utilize Proportional-integral-derivative (PID) or modified PID control schemes, which can offer the simplest and yet most efficient solution [3].

The concept of a disturbance observer has been widely used in disk drive servo control system to compensate for system disturbances and error of modeling [4, 5].

In order to get stable and reliable control algorithm for the complicated TC-1 heater control, the disturbance observer based PID control algorithm using ON/OFF scheme is presented in this paper. This proposed control algorithm is implemented and tested by Simulink and an actual furnace, which has similar thermal characteristic of the heaters in TC-1.

II. Disturbance Observer Based PID Control Designing

Many control systems have their own big or small disturbance sources according to their structure and objective. Inside the TC-1 loop, the electromagnetic pump used for molten metal circulation, particularly due to its low efficiency, becomes a big heat source to these heating zones. Besides, the operation of cover gas system will introduce cool gas into the loop, which could be another contribution of external disturbance.

The disturbance observer (DO) based control methods can be used to compensate modeling uncertainties as well as external disturbance. The disturbance observer regards the difference between the actual output and output of the nominal model as an equivalent disturbance applied to the nominal model. Fig.2 shows the block diagram of disturbance observer based control. The basic controller and disturbance observer will be designed in this paper.

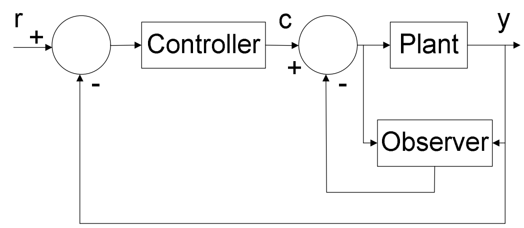

Fig. 2. Disturbance observer based control.

The thermal characteristic of the furnace was obtained from the pulse response prior to the controller design.

II.A. System Identification

Based on the data from pulse response, the system is identified. As for small less thermal stress due to temperature difference, the pulse response of heaters in TC-1 will be obtained under the condition that temperature will not exceed to 90 degree, which is the highest temperature close to target setting temperature (200 °C). Therefore, the same experimental condition will be kept for the furnace system identification. Based on the system identification, the approximate plant model of this single heating zone will be derived.

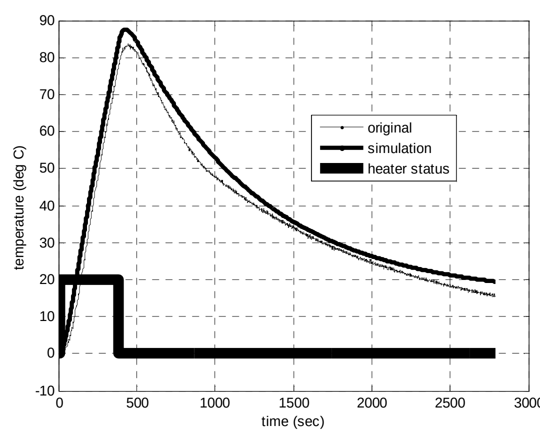

Fig.3. System identification data

The identification results (simulation curve) and original data are shown in Fig. 3. In both the heating and cooling processes, the identification result is close to the original data.

The transfer function of the identified result is:

$$p = \frac{0.008025s + 1.352^{-6}}{s^3 + 0.02872s^2 + 3.362^{-5}s} \quad (1)$$

This model is used as the system plant to serve the controller and disturbance designing.

II.B. PID Control Tuning

To take advantage of proportional control, integral control, and derivative control, the combination of them, Proportional-plus-integral-plus-derivative control action, or PID control, is used in this paper. The transfer function of this controller is given by

$$\frac{U(s)}{E(s)} = K_p(1 + \frac{1}{T_i s} + T_d s) \quad (2)$$

where K_p is the proportional gain, T_i is the integral time, and T_d is the derivative time.

With the available plant model, one Ziegler-Nichols tuning rule is used to get the PID gains. We first set T_i as infinity and T_d as zero, use the proportional control action only, and increase Kp from 0 to a critical value K_{cr} where the output first exhibits sustained oscillations [6]. Thus the critical gain K_{cr} and a corresponding period P_{cr} are experimentally determined. In this paper, K_{cr}=1250, P_{cr}=2s, Ziegler-Nichols tuning rule is used as the following equations to determine the values of these parameters K_p, T_i, T_d.

$$K_p = 0.6K_{cr},\ Ti = 0.5P_{cr},\ T_d = 0.125Pcr \quad (3)$$

The corresponding PID gains for our plant model are K_p=750.000, T_i=1.000, T_d=0.250. Programs were made in Simulink toolbox of MATLAB to test these gains and its simulation result met both the small overshoot and stability requirements.

Based on these calculated values, we will also adjust properly these values when we make the control on the actual heating zone if necessary. This is reasonable in that there is inevitably more or less error between our identified plant model and the actual system, while those calculated values just came from that identified plant model.

II.C. Disturbance Observer

Fig. 4 shows the complete block diagram of disturbance observer based PID control. The part in Fig.4with dash line around shows a disturbance observer loop. Signals c, d, n, and y are the command, disturbance, noise, and output respectively. Signal $\hat{d}$ and $\hat{d}_f$ are the disturbance estimate before and after being filtered by the low-pass filter Q. The command c is provided by an outer loop controller. As in Fig. 2, it is the direct output of controller. G_p is the actual plant; G_n is the nominal plant model. The disturbance observer itself, which is surrounded by the dotted line, estimates disturbance $\hat{d}$ from the plant's output y and plant's input.

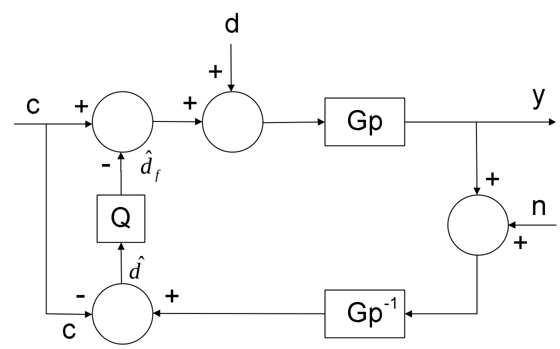

Fig. 4. Disturbance Observer

The filtered signal u of the disturbance observer input and the noise input is determined only the plant dynamics Gp and the nominal model G_n. The function of nominal model is to be selected for both good steady state accuracy and transient response to the low frequency disturbance like some constant disturbance. Simultaneously, it is supposed to be designed for good noise rejection.

The general expression of G_n is as follows

$$G_n = \frac{1}{a_0 s^m + a_1 s^{m-1} + \cdots + a_{m-1}s + a_m} \quad (4)$$

In this research, the nominal plant model Gn is chosen as a low order approximation of the actual plant. Q is designed to trade-off disturbance and parameter rejection against noise and stability robustness.

Using Gopinath's method, the disturbance model is consider as $\hat{d} = \frac{1}{s^k}$, and then Q is given by [7]

$$Q(s) = \frac{g_{m+k-k}s^{k-1} + \cdots + g_{m+k-2}s + g_{m+k-1}}{s^{m+k-1} + g_1 s^{m+k-2} + \cdots + g_{m+k-2}s + g_{m+k-1}} \quad (5)$$

In this paper, we adopt the step disturbance model, i.e. k=1.

Here for control on one heating zone, the convectional velocity type of disturbance observer is referred to. The observer function of Gn^{-1} is only a constant. The average natural heating rate of the zone without control is utilized as the element of G_n and then the value of element of G_n^{-1} is available by the reciprocal value.

III. Experimental Results and Discussion

One furnace with similar thermal characteristic of the heaters in TC-1 was employed as the simulator. The furnace was controlled by a solid state relay in one small control box, which is connected via cable to the Data Acquisition system from National Instrument Inc. The disturbance observer based PID control algorithm is achieved by using LabVIEW program.

In TC-1 system, all heaters are only ON/OFF controlled using solid state relays, which receive control signals from computer. There are not interim values for heater control. The PID interim control output between ON and OFF can be obtained with the Pulse Width Modulation (PWM)[8]. However, the frequent ON and OFF command output can lead to wear in the final control element, such as the mechanical relay in NI SCXI 1161 relay control device and solid-state relay for heater. One medium value is carefully selected to truncate PID output to zero if output is less then it, and round toward 1 if PID output is bigger than the medium value.

One arithmetic average scheme is used as the filter for PID to reduce the random error or noise in the measured process. Resultantly, the PID output fluctuations will also be smoothed.

The sample-period is considered for stability, because the continuous control is replaced by the discrete control using computer. One second finally was selected in comparing with other sample-period, such as 0.5 and 3 seconds). As shown in Fig. 5, there are significant fluctuations in the temperature profile around setting point, when 3 second sample-period time is applied. While small sample-period will lead to the frequent variation of control output that cause control element wear.

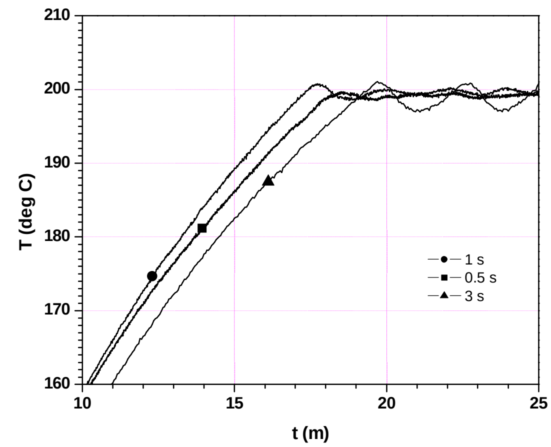

Fig. 5. Control performances under different sample-period (0.5 s, 1 s and 3 s, respectively).

The comparison of the control algorithm with and without disturbance observer was carried out. The disturbance is simulated by open the door of furnace with a small gap for certain of time.

The PID control algorithm has an excellent performance with no overshot and with a very fast decay to the final steady state within 0.7% of the setting point. As a sacrifice, it took about 21 minutes to settle down to the setting point (see Fig. 6).

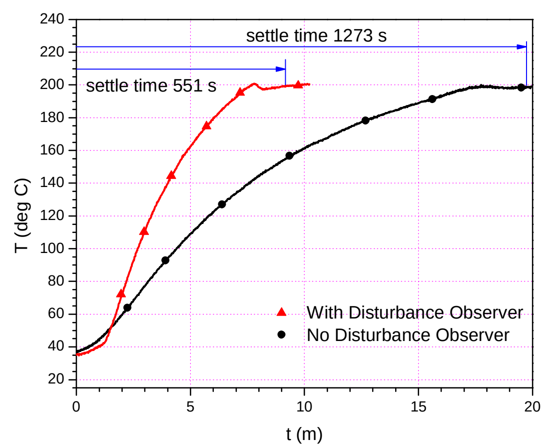

Fig. 6. Heating up process with and without disturbance observer.

The disturbance observer works as a significant role of determining disturbance suppression performance of the system. The heating processing from room temperature to setting point (here 200 °C) are shown in Fig. 6 under the conditions of with and without disturbance observer. As the disturbance observer is involved in the control process, the heating-up process speeds up with only about 9 minutes approaching to the setting point. However, 0.4% peak overshot ratio based on the setting point is noticed, but can be neglected.

Under the condition with thermal disturbance, the PID control algorithm responses immediately with temperature reducing. However, the deviation from setting point trigs the PID control, which pulls back the temperature to its setting point. It took 205 seconds that furnace get back to 200°C, while the thermal disturbance still existed. When thermal disturbance removed, temperature has a slightly increase, as shown in Fig. 7.

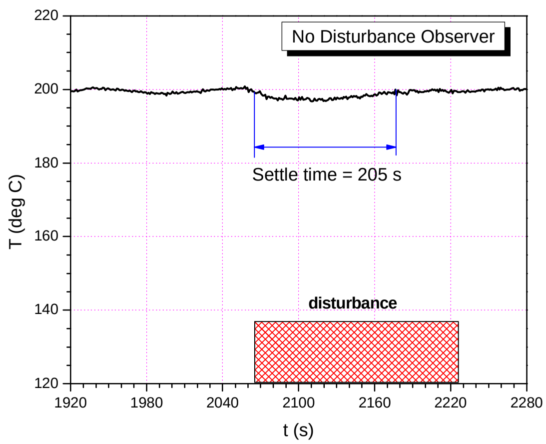

Fig. 7. Performance of PID control with thermal disturbance presented.

The disturbance observer based PID control shows a slag response to the external thermal disturbance with a lag time of 60 seconds. The thermal disturbance rejection is obvious that it only took 97 seconds to make the temperature returning to setting point (see Fig 8).

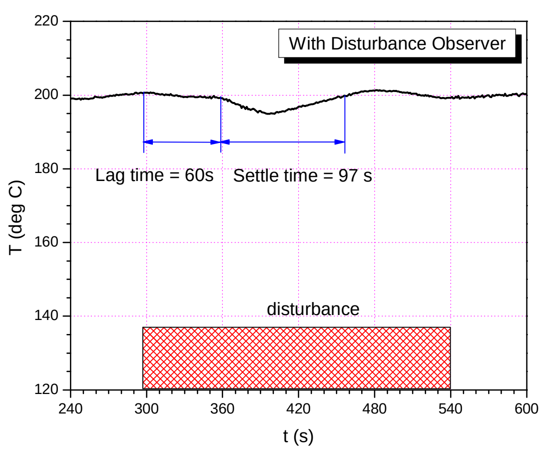

Fig. 8. Performance of disturbance observer based PID control with thermal disturbance presented.

Ⅳ.Conclusions

A disturbance observer based PID control algorithm is proposed to compensate modeling uncertainties as well as the external disturbance, due to the structure complexity of TC-1 loop. The proposed algorithm was implemented and tested by the Simulink and the actual furnace. The corresponding experimental results shows the proposed control scheme is believed to successful track the setting temperature even and reject disturbance.

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REFERENCES

1. E. Yefimov, B. Gromov, and V. Stepanov, *"Thermal and Engineering Tests of Target Complex,"* IPPE, Russia, (2001).
2. W.K Roots. and J.T. Woods, *"On-Off Control of Thermal Processes,"* IEEE Transactions on Industrial Electronics and Control Instrumentation, **EDCI-16** (2), p. 136-146, (1969).
3. K. K. Ang, G. Chong, and Y. Li, *"PID Control System Analysis, Design, and Technology,"* IEEE Transactions on Control Systems Technology, **13** (4): p. 559-576, (2005).
4. Y Huang and W. Messner, *"A Novel Disturbance Observer Design for Magnetic Hard Drive Servo System with a Rotary Actuato,"* IEEE Transactions on Magnetics, **34**(4): p. 1892-1894, (1998).
5. J.S. Lee, H. Suh, B.J. You, and S.R. Oh, *"A Novel Visual Servoing Approach involving Disturbance Observer*, in *International Conference on Robotics & Automation,"* Detroit, Michigan, p. 269-274, (1999).
6. K Ogata, *Modern Control Engineering*. 2nd ed. pp. 672-673, Prentice Hall International, Inc, (1997).
7. T Piraisoodi, and S. Sadhu, *"Characteristic Analysis of High Order Disturbance Observer,"* in *IEEE Indicon Conference*, Chennai, India, 11-13 Dec, p.431-436, (2005).
8. M. B. Sandler, *"Digital-to-analogue Conversion using Pulse Width Modulation,"* Journal of Electronics & Communication Engineering, p. 339-348, (1993).