Process parameter estimation and temperature control of a reactor with high thermal inertia

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ABSTRACT - This research was done for temperature control of a reactor with high thermal inertia. The reactor chamber temperature is required to be critically controlled at 300^0C. A non-linear thermodynamic model was developed, and process parameters were estimated to comply with experimental data by numerical optimization. In practice, a single sensor control system is the only possible option for this reactor. Therefore, the cascade controller was implemented with a predicted temperature reading.

Keywords: System identification; Numerical simulation; Temperature controlling; PID; Cascade

INTRODUCTION

Temperature controlling is widely used in process engineering. Most of the systems can be controlled with simple controllers such as on and off mechanism or PID (Bequette, 2003). When the system becomes more robust, controlling is difficult and advanced control systems are required. In this study, control system was developed to control the temperature of a lab scale torrefaction reactor

The 3kW electrical heater was controlled by a PWM signal. This system responds very slowly as its thermal inertia is very high. The heat transfer process of the system was identified by modelling and the control mechanism was simulated in MATLAB/SIMULINK (Ong. M. C, 1997) environment and a suitable control structure was developed.

METHODOLOGY

Process Parameter Estimation

A mathematical model was developed considering heat transfer of the reactor (BERGMAN, LAVINE, INCROPERA, & DEWITT, 1385). The heater and the reactor chamber were considered as two subsystems. Heat transfers of the system are shown in Figure 1.

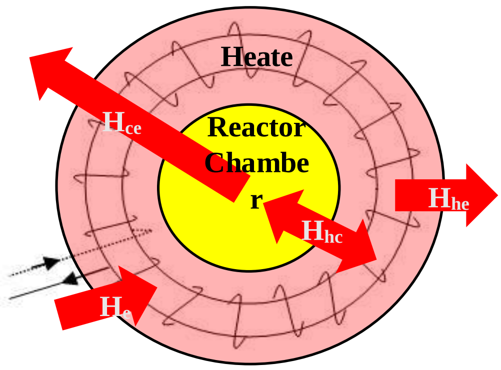

Figure 1. Heat transfers of the system

Energy balance of each unit was considered separately. The heater part was considered as a hollow cylinder.

A dead time (τ_d) was observed from experimental data and the experimental value was incorporated with the model (Tyreus & Luyben, 1992). By experiments, it could be observed that the dead time (τ_d) has an inverse relationship with the Duty cycle of PWM input to the heater.

$$\tau d = k_d \frac{1}{P} \quad (1)$$

Then a mathematical model of the heater can be built as,

$$C_h \frac{dT_h}{dt} = H_e - H_{hc} - H_{he} \quad (2)$$

H_e - Heat provided by the electricity
H_{hc} - Heat transfer from the heater to the reactor chamber
H_{he} - Heat loss from the heater
C_h - Thermal capacity of the heater

$$C_h \frac{dT_h}{dt} = IVP - \frac{2\pi Lk(T_h - T_c)}{l(\frac{r_2}{r_1})} \times f_{\tau_d}(t) - h.2\pi r_2 L(T_h - T_e) \quad (3)$$

H_e - Heat provided by the electricity
I – Current
V – Voltage
P – Duty cycle of PWM
k - Heat conductivity between heater and reactor chamber
T_h – Temperature of the heater
T_c – Temperature of the reactor chamber
T_e – Temperature of the environment
L – Length of the heater
r_1 – Inner radius of the heater
r_2 – Outer radius of the heater
h – Convection heat transfer coefficient
$f_{\tau d}(t)$ is a step function such that

$$f_{\tau d}(t) \begin{cases} 0 \text{ if } t<\tau_d \\ 1 \text{ if } t>\tau_d \end{cases}$$

$$\frac{dT_h}{dt} = n_1 P - n_2(T_h - T_c) \times f_{\tau_d}(t) - n_3(T_h - T_e) \quad (4)$$

The reactor chamber is cylindrical, and it is covered by the heater. Therefore, heat loss can be considered only through the two flat surfaces. Then heat enters the reactor through the cylindrical surface.

Heat balance of the heater is,

$$C_c \frac{dT_c}{dt} = H_{hc} - H_{ce} \quad (5)$$

H_{ce} - Heat loss from the reactor chamber

C_c - Thermal capacity of the reactor chamber

$$C_c \frac{dT_c}{dt} = \frac{2\pi Lk(T_h - T_c)}{ln ln\left(\frac{r_2}{r_1}\right)} \times f_{\tau_d}(t) - h.2\pi r_1^2(T_c - T_e) \quad (6)$$

$$\frac{dT_c}{dt} = n_2(T_h - T_c) \times f_{\tau_d}(t) - n_4(T_c - T_e) \quad (7)$$

Here; n_1, n_2, n_3 and n_4 are the system parameters. In this study, these parameters were empirically determined for the rector.

In the experiment, temperature variation inside the reactor chamber was recorded for 70 minute period, when the heater was powered by 40% PWM duty cycle for a 10 minutes pulse.

The system parameters of n_1, n_2, n_3, n_4 were numerically estimated by using least squares error (LSE) method. Gradient descent algorithm (Rumelhart, Hinton, & Williams, 1986) was used for minimizing the objective function (SE).

Temperature Controlling of the Reactor

The control error (E) of the system can be defined as,

$$E = T_{c\,set} - T_c \quad (8)$$

$T_{c\,set}$ – Setpoint of the reactor chamber (300^0C)

The proposed controllers were tuned for minimizing the Integral Squares Error (ISE) of the system by using gradient descent algorithm. Then, ISE is defined as,

$$ISE = \int_0^T E^2\, dt \quad (9)$$

Single loop PI controller (Controller 1)

$$u = k_P.E + k_I \int E \quad (10)$$

Where k_p and k_I are constants, which are required to be tuned for controlling the system.

Cascade controller (Controller 2)

Traditional cascade controlling mechanism (Zhang, Zhang, Ren, Hou, & Fang, 2012) (Controller 2) was developed by considering secondary loop measurement as temperature of the heater.

Cascade controller with a single sensor and predicted Th (Controller 3)

As it is not feasible to measure the temperature of the heater because of its physical structure, it was predicted by using following formula,

$$T_{h\,pred} = \frac{\frac{dT_c}{dt} + n_4(T_c - T_e)}{n_2} + T_c \quad (11)$$

$T_{h\,pred}$ – Predicted temperature of heater

RESULTS

The performance of the controllers is shown in Table 1.

Table 1. Performance of controllers

Controller	ISE (for 2 hours)	Stabilizing Time (minutes)
Controller1	3.4851×10^7	60
Controller2	3.4245×10^7	40
Controller3	3.4245×10^7	40

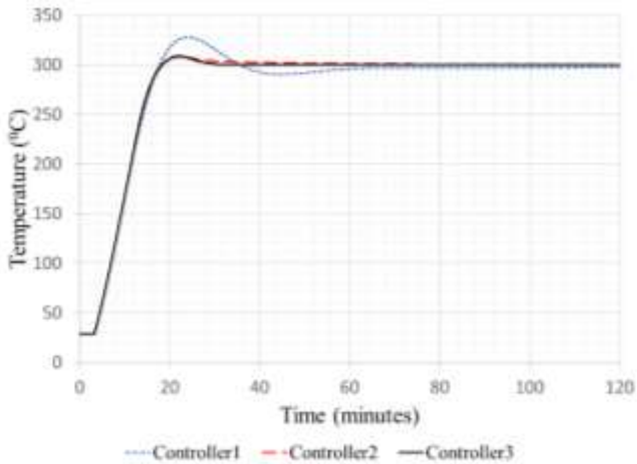

Figure 2. Comparison of controllers

CONCLUSION

As results show, cascade controlling can be used for controlling systems with high time constant.
When it is not feasible to install two sensors, predicted value can be used with a single sensor for cascade controlling algorithm.

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