Thermal control for the liquid metal coolant circulation loop

Xiuju Tan
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THERMAL CONTROL FOR THE LIQUID METAL COOLANT CIRCULATION LOOP

By

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A thesis submitted in partial fulfillment
of the requirement for the

Master of Science Degree in Mechanical Engineering
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ABSTRACT

Thermal Control for the Liquid Metal Coolant Circulation Loop

By

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The target complex facility (TC-1 facility) located at University of Nevada, Las Vegas (UNLV), is serving the fundamental research of thermal-hydraulics and corrosion test of liquid metal coolant lead bismuth eutectic (LBE). A stable thermal condition is the basis for the TC-1 facility to operate and target coolant LBE to circulate throughout the loop made of the main components of TC-1 facility, TC-1 loop. The proper thermal process of the TC-1 loop critically comprises a smooth heating phase, the main intention of which is to warm all the loop components and melt solid LBE; a stable temperature maintenance phase, which is to maintain the TC-1 loop temperature around the setting point to make sure target coolant circulates efficiently for long time; and a cooling phase, which to make sure coolant be stored inside a certain component drainage tank as solid state after the circulation finishes.

The current thermal control scheme for the TC-1 loop has a very low efficiency.
Under the current control, many problems happen to the important temperature maintenance phase. For example, heating zones’ temperature of the TC-1 loop vibrates seriously, some heating zones’ vibration range is much bigger than accepted, and to the worst some zones’ temperature vibrate outside the setting range. All these problems affect inversely the further research of hydraulics and corrosion of liquid metal coolant.

In this thesis, the system identification method has been used to identify system mathematical model. Based the identified system models, different control schemes are studied and demonstrated. Current control scheme of band temperature control is investigated again, then two new thermal control schemes are proposed for the TC-1 loop, one of which is a hybrid scheme of proportional-plus-integral-plus-derivative control scheme (PID control) and ON/OFF control, the other is a disturbance observer (DOB) based PID-ON/OFF control scheme.

Moreover, the performance of the current control scheme and proposed control schemes is demonstrated for the nine heating zones separately as well as a simulator furnace by simulation method through SIMULINK toolbox under the MATLAB environment. Finally, guided by the obtained simulation results, many experiments corresponding to these different control schemes for the heating zones of the TC-1 are performed on the furnace using the commercial National Instrumental LABVIEW.

The obtained experimental results from the simulator can be used as a guideline and reference for the further experiments in the TC-1.
TABLE OF CONTENTS

ABSTRACT ............................................................................................................................. iii
TABLE OF CONTENTS ......................................................................................................... v
LIST OF FIGURES ............................................................................................................... vii
ACKNOWLEDGEMENTS .................................................................................................... ix
CHAPTER 1 INTRODUCTION AND BACKGROUND ................................................... 1
  1.1 Target Complex Facility (TC-1 Facility) ............................................................... 1
  1.2 Thermal Process and Circulation Process of TC-1 Loop ........................................ 4
  1.3 Data Acquisition and Control Program .............................................................. 8
  1.4 Control Schemes in Thermal Process .................................................................. 11
  1.5 Purpose of this Study ....................................................................................... 14
CHAPTER 2 CONTROL SCHEME AND METHODOLOGY ...................... 16
  2.1 System Identification and System Mathematical Model ....................................... 16
  2.2 Theoretical Analysis on Different Control Schemes ............................................. 19
    2.2.1 ON/OFF Control Scheme ................................................................................. 19
    2.2.2 Existing ON/OFF Based Band Control Scheme ............................................. 20
    2.2.3 PID Control Actions ....................................................................................... 22
    2.2.4 Combination of PID and ON/OFF ............................................................ 25
    2.2.5 Disturbance Observer (DOB) ........................................................................... 27
    2.2.6 Disturbance Observer Based PID-ON/OFF Control ....................................... 31
CHAPTER 3 RESULTS AND DISCUSSION................................................................. 34
  3.1 Simulation Results of Thermal Process under Current Control Scheme .......... 34
    3.1.1 Simulation Results of Thermal Process of TC-1 under Current Control Scheme .................................................................................................................. 34
    3.1.2 Simulation Results of Thermal Process of Simulator Furnace using Band Control ............................................................................................................................ 45
  3.2 Simulation Results of Thermal Process using Hybrid PID-ON/OFF Control .... 48
    3.2.1 Simulation Results of Thermal Process of TC-1 using PID-ON/OFF Control .................................................................................................................. 48
    3.2.2 Simulation Results of Thermal Process of Simulator Furnace using Hybrid PID-ON/OFF Control Scheme ..................................................................................... 68
  3.3 Simulation Results of Thermal Process under DOB Based PID-ON/OFF Control .................................................................................................................. 71
    3.3.1 Simulation Results of Thermal Process of TC-1 using DOB based PID-ON/OFF Control .................................................................................................................. 71
    3.3.2 Simulation Results of Thermal Process of Simulator Furnace using DOB
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.</td>
<td>Target Complex facility. [5]</td>
</tr>
<tr>
<td>Figure 2.</td>
<td>TC-1 loop in 2-dimensions</td>
</tr>
<tr>
<td>Figure 3.</td>
<td>Block diagram of the thermal process of TC-1</td>
</tr>
<tr>
<td>Figure 4.</td>
<td>Natural thermal process of TC-1 zone 4</td>
</tr>
<tr>
<td>Figure 5.</td>
<td>System identification</td>
</tr>
<tr>
<td>Figure 6.</td>
<td>Band temperature control</td>
</tr>
<tr>
<td>Figure 7.</td>
<td>Block diagram of a PID control</td>
</tr>
<tr>
<td>Figure 8.</td>
<td>Block diagram of the hybrid PID-ON/OFF control</td>
</tr>
<tr>
<td>Figure 9.</td>
<td>Relationship between relay status and ON/OFF control</td>
</tr>
<tr>
<td>Figure 10.</td>
<td>Block diagram of full-order observer for a linear process</td>
</tr>
<tr>
<td>Figure 11.</td>
<td>Block diagram of disturbance observer</td>
</tr>
<tr>
<td>Figure 12.</td>
<td>Block diagram of disturbance observer based control system</td>
</tr>
<tr>
<td>Figure 13.</td>
<td>Thermal process of zone 1 with band control (13.a, 13.b, 13.c, 13.d)</td>
</tr>
<tr>
<td>Figure 14.</td>
<td>Thermal process of zone 2 with band control (14.a, 14.b, 14.c, 14.d)</td>
</tr>
<tr>
<td>Figure 15.</td>
<td>Thermal process of zone 3.1 with band control (15.a, 15.b, 15.c, 15.d)</td>
</tr>
<tr>
<td>Figure 16.</td>
<td>Thermal process of zone 3.2 with band control (16.a, 16.b, 16.c)</td>
</tr>
<tr>
<td>Figure 17.</td>
<td>Thermal process of zone 4 with band control (17.a, 17.b, 17.c)</td>
</tr>
<tr>
<td>Figure 18.</td>
<td>Thermal process of zone 5 with band control (18.a, 18.b, 18.c, 18.d)</td>
</tr>
<tr>
<td>Figure 19.</td>
<td>Thermal process of zone 6 with band control (19.a, 19.b, 19.c, 19.d)</td>
</tr>
<tr>
<td>Figure 20.</td>
<td>Thermal process of zone 7 with band control (20.a, 20.b, 20.c, 20.d)</td>
</tr>
<tr>
<td>Figure 21.</td>
<td>Thermal process of zone 8 with band control (21.a, 21.b, 21.c, 21.d)</td>
</tr>
<tr>
<td>Figure 22.</td>
<td>Furnace (outside and inside)</td>
</tr>
<tr>
<td>Figure 23.</td>
<td>Natural thermal attributes of furnace and zone 8</td>
</tr>
<tr>
<td>Figure 24.</td>
<td>Thermal process of simulator with band control (24.a-24.f)</td>
</tr>
<tr>
<td>Figure 25.</td>
<td>Thermal process of zone 1 with hybrid PID-ON/OFF control (25.a-25.d)</td>
</tr>
<tr>
<td>Figure 26.</td>
<td>Thermal process of zone 1 with disturbance using hybrid PID-ON/OFF control (26.a, 26.b, 26.c)</td>
</tr>
<tr>
<td>Figure 27.</td>
<td>Thermal process of zone 2 with hybrid PID-ON/OFF control (27.a-27.d)</td>
</tr>
<tr>
<td>Figure 28.</td>
<td>Thermal process of zone 2 with disturbance using hybrid PID-ON/OFF control (28.a, 28.b, 28.c)</td>
</tr>
<tr>
<td>Figure 29.</td>
<td>Thermal process of zone 3.1 with hybrid PID-ON/OFF control with disturbance (27.a-29.d)</td>
</tr>
<tr>
<td>Figure 30.</td>
<td>Thermal process of zone 3.1 with hybrid PID-ON/OFF control with disturbance (30.a, 30.b)</td>
</tr>
<tr>
<td>Figure 31.</td>
<td>Thermal process of zone 3.2 with disturbance using hybrid PID-ON/OFF control (31.a-31.d)</td>
</tr>
<tr>
<td>Figure 32.</td>
<td>Thermal process of zone 3.2 with hybrid PID-ON/OFF control with disturbance (32.a, 32.b)</td>
</tr>
</tbody>
</table>
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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Target Complex Facility (TC-1 Facility)

Lead bismuth eutectic (LBE) is a binary alloy of lead (Pb) and bismuth (Bi) (about 45 wt% of Pb and 55 wt% of Bi). Currently, LBE is of strong interest worldwide as an ideal nuclear coolant and high-power spallation material in accelerator driven systems (ADS) due to its favorable thermal-physical and chemical properties, such as, low melting point (about 123.5°C), high boiling (about 1670 °C), low vapor pressure, good neutron yield, fast heat removal as well as chemical inertness resulting in no reaction with air or water. [1] However, the corrosiveness of the lead-alloys is a critical obstacle and challenge for safe applications in reactors and ADS. The challenging studies on the corrosiveness of LBE and protective technology have attracted abundant efforts from researchers and research groups all over the world. [2] [3] [4]

The target complex facility (TC-1 facility) was designed by Russian specialists of Institute of Physics and Power Engineering (IPPE) and Experimental and Development Organization (EDO) for nuclear waste treatment in 1998. Later it was a part of the experimental facility for proton beam testing in the accelerator at Los Alamos Neutron Science Center (LANSCE). In June 2002, it was delivered to University of Nevada, Las
Vegas (UNLV). The initial objective of UNLV was for irradiating research. However, the irradiating facility was not available in UNLV; the initial objective was given up. Moreover, no accelerator is available in UNLV. Therefore the target complex facility has been located for the fundamental research of thermal hydraulics and corrosion test of liquid metal coolant LBE.

![Diagram of Target Complex facility](image)

**Figure 1.** Target Complex facility. [5]

The intention of the TC-1 facility is to supply certain conditional target coolant LBE
to circulate in a loop made of the major components of the target complex facility. The TC-1 facility is shown as figure 1.

The target coolant circulation loop (TC-1 loop) consists of components such as the target part, magnetic hydro-dynamics-pump (MHD-pump), volume compensator (VC), heat exchanger (HE), drainage tank (DT), siphon interruption device (SID), pipes, as well as many sensors and cables. TC-1 components and pipelines have tens electric heaters and the heaters are surrounded with thermal insulation (except the target part). All the heaters are resistance heaters and made of chromium-nickel alloy wire. [5]

The components and pipelines of TC-1 are schemed as: primary circuit, cover gas system of primary circuit, heat exchanger cooling system, and internal shielding cooling system. The primary circuit components consist of the target part, magnetic hydro-dynamics pump, heat exchanger, volume compensator, drainage tank, siphon interruption device, and main and auxiliary pipelines. The intension of primary circuit is to provide coolant circulation through the target part and remove the heat released in the target part into the heater exchanger cooling system. The primary circuit comprises the circulation loop and the drainage tank, which are connected with each other by pipelines for filling and draining through siphon interruption device.

The proton beam will be introduced horizontally into the target through a water-cooled steel window installed in the container. Inside the target, proton beam will interacts with spallation material and target coolant LBE to generate neutrons required for the accelerator driven system.

All the components of TC-1 are placed in the cavity of a sealed container, as shown in Figure 1, which is a steel rectangular cross-section box with the dimensions of
640*710*4075mm. The container is intended for the coolant localization in the events of accidents with target circuit tightness failure.

1.2 Thermal Process and Circulation Process of TC-1 Loop

TC-1 components and pipelines have electric heaters and they are surrounded with thermal insulation except the target part. As in figure 2, there are nine heating zones for the TC-1 loop, which are zone 1—upper part of drainage tank; zone 2—lower part of drainage tank; zone 3.1—upper part of heat exchanger; zone 3.2—lower part of heater exchanger, zone 4—MHD-pump with head pipeline; zone 5—volume compensator with drain air pipeline to heat exchanger; zone 6—target with “hot” pipeline; zone 7—pipeline primarily filling up the circuit with the coolant, pipeline pressurizing the coolant from drainage tank to the circuit and vice versa, and pipelines of the cover gas system; zone 8—siphon interruption device SID, pipelines in the TC-1 lid area including pipeline of primary filling up the circuit and pipe of the cover gas system.

Each heating zone has its own main heater and a backup heater. All the electric heaters are resistance heaters made of chromium-nickel alloy wire. The heaters are arranged on external surface of TC-1 components and pipelines. Total power of the electric heaters is 17.5kW. [5]

The overall thermal process comprises three main phases: the preparation phase—heating phase; the running phase—temperature maintenance phase; and final phase—cooling phase. Figure 2 shows the block diagram of the thermal process of the TC-1 loop. The thermal process includes the heating phase, the temperature maintenance phase and
the natural cooling phase.

Figure 2. TC-1 loop in 2-dimensions

The heating phase comprises several sub-phases. In the heating phase, zone 1 is activated first. When zone 1 is hotter than zone 2 by 50 °C, all other zones are also activated. When zone 1 reaches about 125 °C, LBE in zone 1 melts. Later when zone 2 reaches the melting point, LBE in zone 2 melts. Then all zones will be heating to the setting point and temperature maintenance phase starts. Liquid coolant is pressured out from drainage tank to fill the primary and then circulation process runs throughout the
primary loop during the long time temperature maintenance phase. When the circulation process completes, liquid coolant LBE will be pressured back to the drainage tank. Finally, after natural cooling phase, LBE will be stored in the drainage tank in solid state.

1. Heating phase
   - Heater of zone 1 starts working.
   - When $T_1 - T_2 = 50^\circ C$, other zones' heaters also start to work.
   - $T_1 \sim 123.5^\circ C$, LBE in zone 1 melts
   - $T_2 \sim 123.5^\circ C$, LBE in zone 2 melts
   - Zones reach the setting point
2. T maintenance phase
   - Temperature maintains around the setting point.
3. Cooling phase
   - Circulation ends, and cooling starts

Figure 3. Block diagram of the thermal process of TC-1

Thermal and engineering monitoring of TC-1 is realized by means of instrumentation system including thermocouples, electro contact level meters and electromagnetic flow meter. Thirty-seven regular thermocouples are installed on TC-1 components and pipelines. Twenty-nine thermocouples are installed on the components surface and 8
thermocouples in sealed sockets are immersed into coolant. In each heating zone, two thermocouples are installed: one is for control and the other is for protection. To improve TC-1 monitoring during tests, additional ten thermocouples are installed on TC-1 components.

To provide power of 90V 60Hz necessary for these TC-1 electric heaters, one phase step-down transformers and one-phase autotransformers are used. In the circuit part developed by Los Alamos National Laboratory, nine heater sections are divided into two groups. Each group has a “connection-disconnection and protection” apparatus-automatic circuit breaker. Each section has high-speed switch relay, which disconnects electric heaters under loss of insulation resistance.

Power equipment of the TC-1 heating system is installed in a box developed and manufactured by LANL. 90V/120V transformer and two rectifiers with ±12V output are also installed to feed the programming relays. Operation program periodically triggers the automatic timer with constant frequency. In the case of the failure of the program, this timer snap into action the relay in 10 seconds, which breaks the 12-V contacts; and MHD-pump and TC-1 heating system are automatically disconnected.

TC-1 is heated up by means of switching on heating zones. Before heating, TC-1 circulation loop is filled with argon with pressure of 10 kPa. Temperatures are controlled by switching on/off the zones according to the following requirements:

1. Not allow heating rate more than 50°C/hr;
2. Not allow temperature difference between any two zones bigger than 20°C. [5]

TC-1 control and parameter regulation system provides parameter control and automatic regulation-parameter maintenance. Control algorithm for heating up and
temperature regulation in nine heating zones is realized by executive devices-solid relays that switch on/off the heaters in accordance of the data acquisition (DAC) system algorithm. The algorithm provides the given rate of the zones heating, keep the zone temperatures in given intervals, automatic maintenance this temperature in the interval. [5][6]

There is a mimic panel on PC display, where the nine sections of the TC-1 heating system are schematically shown. Heaters in operation are marked by red, non-operating ones by violet. Control and protective thermocouples are also presented on PC-display.

1.3 Data Acquisition and Control Program

The LANL Accelerator Transmutation of Waste and DOE Advanced Accelerator Applications programs have invested in developing LBE technology for spallation target and nuclear coolant applications since 1997. Currently, there is one standby LBE hydraulic test loop, one LBE material and thermal hydraulic test loop under construction. In the ISTC project #559 a 1-MW LBE spallation test target was designed and fabricated in Russia, and was assembled and tested out-of-beam. Among these loops, the control of them is the basis. Data acquisition, electrical, thermal (heaters) and emergency response valves, and shutdown procedures should be automated. Configuration valves, variable heat exchanger, cooling water, gas and ventilation systems need to be automated. Pump automatic restart, if available, should be designed. [3]

Data Acquisition and Control system (DAC) is realized using National Instruments data input and output instrumentation as a computer program written in LabView,
National Instruments™'s graphical data acquisition language.

First the program collects the data from the instrumentation on the loop. There are thermocouples, level sensors, pressure transducers, oxygen sensors, flow meters, gas pressure transducers and flow meters. The status of actuated valves and the pump motor can also be determined. Thermocouples readings are read through four SCXI-1102 32 channel thermocouple amplifiers. The data from the thermocouples is transferred to the computer almost instantly. A panel will be built near the loop enclosure where the thermocouple wires plug into and the other side of the panel connects to SCXI 1102. Using this connection method we can easily change the thermocouples connected to DAC at the loop. [3]

Level in the melt tank, sump tank, calibration tank and expansion tank are measured with different length metal rods inserted into the vessels. They are attached at the top with electrode feed-through that insulate them from the tank. Once liquid Lead–Bismuth reaches the end of a rod, it closes an electrical circuit between the tank wall and the rod and the voltage applied to the rods produces a current that is read and sent to the DAC program via an analog input module on SCXI 1100 data acquisition chassis. A magnetic flow meter measures the liquid lead bismuth flow speed. The liquid metal flows between two parallel permanent magnets and induces an electrical fluid perpendicular to the flow and to the magnet poles. Thus, two electrodes welded into the wall of the pipe diametrically opposite to each other and located on a line perpendicular to a line between the magnet’s poles read a voltage that is proportional to the flow speed. Under the flow meter is a pipe leading to the Calibration tank. This arrangement allows us to calibrate the flow meter.
There is a venturi in a loop bypass line near the Sumo Tank that also allows us to measure fluid low. There is a standard expression relating the pressure measurements from a differential pressure transducer at the venturi and the flow speed. Fluid pressure is also measured in the pipe before the venturi and near the Sump Tank right after the pump outlet.

The loop pipes are covered with tape heaters. The melt tank has its own heaters that consist of radiation heater panels arranged around the tank in a cylindrical shape. All of these heaters are controlled from the computer. The regulation in most cases is done by establishing a goal temperature at a control thermocouple on the loop. The program, then, turns on and off the heaters to maintain the goal temperature. The main portion of pipeline is black, and other parts are colored differently according to their function: calibration tank inlet is khaki green and bypasses are blue-green. The melt tank heater power can be modulated, so its power is shown on slider indicators with values from 0 to 45kW. The heaters on the other vessels including the heat exchanger as well as the recuperates are shown as bars that turn red when the heaters are on and blue then they are off. They are also regulated by control thermocouples. Heaters are separated into 31 zones plus 20 zones for each of the hand gate valves on the loop and 9 main heating zones for the band heaters. Each heater zone has at least two thermocouples.

The pump speed is controlled through an Allen-Bradly controller that accepts input signal from the DAC system. Pump power and speed can be varied and its value shown on the screen. The pump can also be stopped instantly from the computer user interface.

Three actuated solenoid valves are controlled from the DAC system through a digital on/off module on SCXI-1100. During calibration the Calibration Tank valve closes
instantly when the highest level in the tank is reached. The other two valves are drainage valves and are opened during liquid metal transfer into the loop and drainage. They are linked to the safety subroutines that stop the pump and drain the loop in a variety of emergency and non-emergency conditions. These valves can also be opened by manual controls from the computer. [3][5]

DAC system collects all of the input and output data in files for future examination. It also outputs plots of temperature, flow speed, pressure, oxygen content and any other data desired.

1.4 Control Schemes in Thermal Process

Combination of proportional control action, integral control action, and derivative control action is termed as proportional-plus-integral-plus-derivative control action (PID). This combined action has the advantages of each of the three individual control actions. PID control method is still widely used as a basic control technology for industrial control system due to its well known simple PID control structure. [7][8][9][10]

With its three-term functionality covering treatment to both transient and steady-state responses, PID control action offers the simplest and yet most efficient solution for many actual control problems. Since the invention of PID control in 1910, and the Ziegler-Nichols’ (Z-N) straightforward tuning methods in 1942, the popularity of PID has grown tremendously. [7]

With advances in a wide spectrum of choices for control now offers a wide spectrum of choices for control schemes. However, more than 90% of industrial controllers are still
implemented based around algorithms, particularly at lowest levels, as no other controllers match the simplicity, clear functionality, applicability, and ease of use offered by the PID controller. Its wide application has stimulated and sustained the development of various PID tuning techniques, sophisticated software packages, and hardware modules.

The success and longevity of PID controllers were characterized in a recent IFAC workshop, where over 90 papers dedicated to PID research were presented. [7] With much of academic research in this area maturing and entering the region of “diminishing returns”, the trend in present research and development (R&D) of PID technology appears to be focused on the integration of available methods in the forms of software so as to get the best out of PID control.

Although PID is still the widely used control technique in practical control, it is categorized as a “Classical control theory”. Modern control theory is considered superior technique to classical control theory under an assumption of no model uncertainty. However, model uncertainty and variability do exist in real world. Moreover, state feedback controller sometimes shows some difficulties for example, selecting best poles to assign, handling nonlinearity such as saturation. Modified PID control or combination of PID control and other control gives us more possibility for application and still reserves the advantage of the PID controller. [11][12][13]

Many kinds of modified PID control have been used for different systems. For example, to avoid the set-point kick phenomenon, the derivative action is supposed to be operated only in the feedback path so that differentiation occurs only on the feedback signal but not on the reference signal. In these cases where the reference input is a step
function, both PID control and PI-D control involve a step function in the manipulated signal, for those occasions of which a step change in the manipulated signal is not desirable, I-PD control action can be used, where the proportional action and derivative action are moved to the feedback path so that these actions affect the feedback signal only. Besides, instead of moving the entire derivative control action or proportional control action to the feedback path, it is possible to move only portions in the feedback path, retaining the remaining portions in the feed forward path, and thus the PI-PD control has been proposed. Similarly, PID-PD control can also be considered. In these modified classic control schemes, there is a controller in the feed forward path and another controller in the feedback path. Such control schemes lead to the general two-degrees-of-freedom control scheme. [14]

The research and development of PID and modern control theory brings possibility for the combination of PID control and other control action. Control method of general PID combined with fuzzy control was used to control the temperature and humidity of room in heating, ventilating and air-conditioning system recently. [15] Control method of the combination of general PID and observer was also used for temperature control such as a deionized water heater that is used for semiconductor processing equipment. [16]

In fact, based on the complement of different control actions, some simple control schemes can also be further combined. Besides, relays are used as heater switches in TC-1 loop, so ON/OFF control will be always a part of TC-1 control System. [17] [18] As a low efficient heating process of the current control, [5][6][19] which is actually an ON/OFF based band temperature control, the ON/OFF based PID control scheme, or a kind of hybrid PID-ON/OFF control will be researched for thermal process in this thesis.
For systems with external disturbance or uncertainties, observers are good solution for compensation during control process. [20][21][22][23][24]

1.5 Purpose of this Study

The goal of this thesis is to explore a highly efficient control scheme for the thermal processes, smooth heating phase as well as the most important stable temperature maintenance phase, of the target coolant circulation loop.

In this study, system identification method will be used to get the thermal attributes of systems. The low efficiency heating zone, zone 4 will be identified firstly and then all the other heating zones of TC-1 loop will be identified separately with the same identification method.

Moreover, after a brief theoretical analysis on the loop, which serves the control designing, theoretical analysis will be presented in detail for different control schemes, the classic ON/OFF control scheme and PID scheme, the currently existing control scheme, the proposed PID-ON/OFF control scheme and the disturbance observer based PID-ON/OFF control scheme.

Furthermore, lots of simulation will be done for each heating zones of the circulation loop as well as a simulator furnace with different control schemes. Simulation results of the same zone but with different control schemes as well as some simulation results of different zones will be compared and discussed. Besides, some experiments will be conducted on this simulator furnace to test currently existing control scheme as well as the proposed new control schemes. And then experimental results from the simulator
furnace with different control schemes will be compared and discussed.

Finally, based on the simulation results and the experimental results, some useful conclusions will be drawn; some results from the developed control scheme will be compared with the ideal requirements; and the extended applications of the developed control scheme will be analyzed.
CHAPTER 2

CONTROL SCHEME AND METHODOLOGY

2.1 System Identification and System Mathematical Model

The dynamic model of a system is important for a controller parameters tuning, new controller structures acceptance, and simulation of thermal hydraulic system behavior. System identification as a modeling method is widely used in scientific researches and practical applications. The purpose of system identification in this research is just to get the dynamic model of the system. [25][26][27]

We consider the system having transfer-function

$$G(s) = \frac{B(s)}{A(s)}.$$ (1)

$A(s)$ and $B(s)$ are polynomials in the Laplace transform complex number $s$ as:

$$A(s) = 1 + a_1 s + \ldots + a_n s^n$$ (2)

$$B(s) = b_0 + b_1 s + \ldots + b_m s^m$$ (3)

The coefficients $n$, $a_i$, and $b_i$ in (2)-(3) are totally unknown. However, we have some basic experimental input-output data, and based on its curve characteristics, we can assume the $n$ value, or the order of the system transfer function. We seek to estimate these parameters or the coefficients $a_i$ and $b_i$ in (2)-(3) from sampled input-output data.
In Figure 4, the natural temperature development curve of heating zone 4-MHD pump with head pipe is characterized by a third order function to some degree. The system...
transfer function is assumed to be third order. Using identification program developed in the SIMULINK toolbox of MATLAB commercial software, identified results close to the original experimental results will be available.

Figure 5 shows the identification results. And the transfer function coming from the identification procedure is as following

$$G_4(s) = \frac{7.851 \times 10^{-4} s + 1.969 \times 10^{-8}}{s^3 + 1.66 \times 10^{-2} s^2 + 8.082 \times 10^{-6} s}$$

This function is the Laplace transformation of the ratio of system plant output to plant input. In Figure 5, the curve of simulation result is close to the one of experimental data. The plant transfer function will represent the system in the later design of controller.

Using the same identification method, models of other heating zones of TC-1 loop are shown as the following respectively:

Zone 1, the upper part of drainage tank:

$$G_1(s) = \frac{1.381 \times 10^{-3} s + 6.268 \times 10^{-8}}{s^3 + 3.835 \times 10^{-2} s^2 + 4.731 \times 10^{-6} s}$$

Zone 2, the bottom part of drainage tank:

$$G_2(s) = \frac{4.569 \times 10^{-4} s + 1.17 \times 10^{-7}}{s^3 + 1.975 \times 10^{-2} s^2 + 7.676 \times 10^{-6} s + 2.005 \times 10^{-10}}$$

Zone 3.1, the upper part of heat exchanger:

$$G_{3.1}(s) = \frac{4.1337 \times 10^{-2} s + 2.534 \times 10^{-8}}{s^3 + 4.853 \times 10^{-3} s^2 + 2.041 \times 10^{-6} s}$$

Zone 3.2, the lower part of heat exchanger:

$$G_{3.2}(s) = \frac{5.012 \times 10^{-4} s + 2.538 \times 10^{-8}}{s^3 + 7.166 \times 10^{-3} s^2 + 2.337 \times 10^{-6} s}$$
Zone 5, volume compensator with drain air pipeline to heat exchanger:

\[ G_5(s) = \frac{8.443 \times 10^{-4} s + 3.151 \times 10^{-9}}{s^3 + 9.982 \times 10^{-3} s^2 + 5.982 \times 10^{-7} s} \]  \hspace{1cm} (9)

Zone 6, target with “hot” pipeline:

\[ G_6(s) = \frac{2.9117 \times 10^{-5} s + 1.2697 \times 10^{-10}}{s^3 + 8.462 \times 10^{-4} s^2 + 5.161 \times 10^{-8} s} \]  \hspace{1cm} (10)

Zone 7, pipeline of primary filling up the circuit with the coolant, pipeline of pressurizing the coolant from drainage tank to the circuit and vice versa, and pipelines of the cover gas system:

\[ G_7(s) = \frac{8.371 \times 10^{-4} s + 2.167 \times 10^{-9}}{s^3 + 6.163 \times 10^{-3} s^2 + 2.176 \times 10^{-6} s} \]  \hspace{1cm} (11)

Zone 8, siphon interruption device SID, pipelines in the TC-1 lid area including pipeline of primary filling up the circuit and pipe of the cover gas system:

\[ G_8(s) = \frac{4.1894 \times 10^{-5} s + 2.1754 \times 10^{-10}}{s^3 + 8.121 \times 10^{-4} s^2 + 1.01 \times 10^{-7} s} \]  \hspace{1cm} (12)

2.2 Theoretical Analysis on Different Control Schemes

2.2.1 ON/OFF Control Scheme

A classic on/off controller is characterized by that the actuating element has only two fixed positions, on and off. With the output signal from the controller being \( u(t) \) and actuating error signal being \( e(t) \), the signal \( u(t) \) remains at either a maximum or minimum value, depending on whether the actuating error signal is positive or negative, which can be described as following:
\[ u(t) = U_1, \text{ for } e(t) > 0 \]
\[ = U_2, \text{ for } e(t) < 0 \]  \hspace{1cm} (13)

where \( U_1 \) and \( U_2 \) are constants representing the two signal index. The minimum value \( U_2 \) is usually either zero or negative \( U_1 \). [14]

The ideal on-off thermal controller for heating mode would compare the desired value of temperature (reference input) to the controlled temperature and set \( u(t) \) to 0 or +1 depending upon the relative magnitudes of the reference temperature and the controlled one. Corresponding to the two different signal indexes, many heating device, like relay in this project, switch between work status and rest status.

2.2.2 Existing ON/OFF Based Band Control Scheme

The existing control scheme in this TC-1 loop is based on ON/OFF control and gives a limited gap around the reference temperature to select the heater status. As in Figure 6, the area between the bottom limit line and the top limit line is for the system to work, and else area is not what we want.

Any temperature inside this band meets the working conditions while other temperature values higher than the top limit or lower than the bottom limit are supposed to be avoided. When the former case happens, whether heater should be switched on or off depends on the existing trend of temperature development; while for the later case, the heater should be switched on. During the process temperature lies inside the band, the frequency of switching heaters to and from on and off is supposed to as less as possible to reduce the device wear; besides, the temperature close to the requirement is wanted. So inside the band, when the temperature is in the increasing, do not switch off the heater
work until temperature reaches the top limit. While when the temperature is in the decreasing process inside the gap, do not switch on the heater work until temperature reaches the bottom limit. Besides, a heating rate limitation of 50 °C/hr was also employed in throughout the TC-1 thermal process.

![Band temperature control diagram](image)

**Figure 6. Band temperature control.**

Set the band width as $\Delta T$, top limit temperature as $T_{\text{top}}$, bottom limit temperature as $T_{\text{bottom}}$, reference temperature as $T_r$, and current temperature as $T$. The logic and mathematical model of the on/off based band control is shown in the following:

$$\Delta T = T_{\text{top}} - T_{\text{bottom}}$$  \hspace{1cm} (14)

Case a. At $T \leq T_r - \frac{\Delta T}{2}$, if $\frac{dT}{dt} \leq \frac{50}{3600}$, switch heater to ON status, else, switch heater to OFF status;

Case b. At $T_r - \frac{\Delta T}{2} < T < T_r + \frac{\Delta T}{2}$, if $\frac{50}{3600} \geq \frac{dT}{dt} > 0$, switch heater to ON status;

else, ($\frac{dT}{dt} < 0$ or $\frac{dT}{dt} > \frac{50}{3600}$), switch heater to OFF status.
Case c. At $T_r - \frac{\Delta T}{2} < T < T_r + \frac{\Delta T}{2}$, and $\frac{dT}{dt} < 0$ or $\frac{dT}{dt} > \frac{50}{3600}$, switch heater to OFF status;

Case d. If $T \geq T_r + \frac{\Delta T}{2}$, whatever $\frac{dT}{dt}$ is, just switch heater to OFF status.

Since the ON/OFF control scheme used in this thesis has only two positions, so if the heater is not in ON status, it should be in OFF status without doubt and vice versa. Therefore, in this scheme, the designer can accomplish his control by just defining all the ON status moment or just all the OFF status moment.

The program algorithm of heating rate limitation is realized as followings:

As $C_r$ is current, $C_r$ is current temperature, $Y_i$ is Y intercept, assuming a high goal temperature of 300°C,

$$Y_i = C_r + (300 - C_r) \frac{-C_r}{(300-C_r)*3600} \cdot \frac{50}{3600},$$

Since $C_r$ is not possible to be higher than 300°C, then there should be

$$Y_i = C_r - \frac{50}{3600} \cdot C_r.$$

Therefore when the following condition exists, heating rate is less than 50 °C/hr.

$$\frac{50}{3600} C_r|_{i-n} + Y_i|_{i-n-1} - C_r|_{i-n} > 0$$

2.2.3 PID Control Actions

The transfer function of proportional-plus-integral-plus-derivative (PID) controller is given by
\[
\frac{U(s)}{E(s)} = K_p (1 + \frac{1}{T_i s} + T_d s)
\]  

(18)

where \(K_p\) is the proportional gain, \(T_i\) is the integral time, and \(T_d\) is the derivative time. Figure 7 shows the classic PID control of a plant.

If the plant is so complicated that its mathematical model cannot be easily obtained, then analytical approach to the design of a PID controller is not possible. For this condition, experimental approaches should be resorted to the tuning of PID controllers. However, if the mathematical model of the plant can be derived, then it is possible to apply various design techniques to design a PID controller, or determining parameters of the controller, that will meet the transient and steady-state specifications of the closed-loop system.

Figure 7. Block diagram of a PID control.

Ziegler and Nichols suggested rules for selecting the PID controller parameters (meaning to set values \(K_p\), \(T_i\) and \(T_d\)) based on experimental step responses or based on the value of \(K_p\) that results in marginal stability when only the proportional control action is used. Ziegler-Nichols rules can be applied to the design of systems with known mathematical models. Besides, they are also very convenient when mathematical models
of plants are not known.

There are two main methods for Ziegler-Nichols tuning rules. The first one is characterized by an available S-shaped step-response curve. For the first method to use, the plant should involve neither integrator(s) nor dominant complex-conjugate poles, and then a unit-step response curve may look like an S-shaped curve. With the available S-shaped curve, determine the intersections of tangent line with the time axis and line \( c(t) = k \), and then delay time \( L \) and time constant \( T \) can be derived.

Table 1. Ziegler-Nichols Tuning Rule Based on Step Response of Plant (First Method).

<table>
<thead>
<tr>
<th>controller</th>
<th>Kp</th>
<th>Ti</th>
<th>Td</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>( T/L )</td>
<td>( \infty )</td>
<td>0</td>
</tr>
<tr>
<td>PI</td>
<td>0.9( T/L )</td>
<td>L/0.3</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>1.2( T/L )</td>
<td>2L</td>
<td>0.5L</td>
</tr>
</tbody>
</table>

In this project, the transfer function of the plant was identified, and the plant model involved an integrator, so the other method of Ziegler-Nichols tuning rule should be used. In the second, firstly, set \( T_i = \infty \) and \( T_d = 0 \), then use the proportional control action only, increase \( K_p \) from 0 to a critical value \( K_{cr} \) where the output first exhibits sustained oscillations. The critical gain \( K_{cr} \) and the corresponding period \( P_{cr} \) are experimentally determined when the plant model is not known. One Simulate code is used to determine \( K_{cr} \) and \( P_{cr} \). Then \( K_p, T_i \) and \( T_d \) can be determined using the Ziegler-Nichols rule as Table 2.
Table 2. Ziegler-Nichols Tuning Rule Based on Step Response of Plant (Second Method).

<table>
<thead>
<tr>
<th>controller</th>
<th>Kp</th>
<th>Ti</th>
<th>Td</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Kcr</td>
<td>∞</td>
<td>0</td>
</tr>
<tr>
<td>PI</td>
<td>0.45Kcr</td>
<td>Pcr/1.2</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0.6Kcr</td>
<td>0.5Pcr</td>
<td>0.125Pcr</td>
</tr>
</tbody>
</table>

PID controller tuned by the second method of Ziegler-Nichols rules gives:

\[ G_c(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s\right) \]

\[ = 0.6K_{cr} \left(1 + \frac{1}{0.5P_{cr} s} + 0.125P_{cr} s\right) \] (19)

In this project, \( K_{cr}=1250 \), \( P_{cr}=2s \), for a PID controller, \( K_p, T_i, T_d, K_p = 0.6K_{cr}, T_i = 0.5P_{cr}, T_d = 0.125P_{cr} \), 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.

2.2.4 Combination of PID and ON/OFF

In the fact that the combination of traditional PID control and other control has many advantages over single control and relays are available in this system, the combination of...
PID control and ON/OFF, named by hybrid PID-ON/OFF control here, is researched in this thesis.

![Block diagram of the hybrid PID-ON/OFF control.](image)

Figure 8. Block diagram of the hybrid PID-ON/OFF control.

Figure 8 shows the combination of a traditional PID control and an On/OFF control, where \( r \) is the reference value, \( u_1 \) is the PID control output, \( u_2 \) is the ON/OFF control output, and \( y \) is the system output.

The relationship between these variables is as follows:

\[
U_1(s) = [R(s) - Y(s)][K_p (1 + \frac{1}{T_i s} + T_d s)],
\]

(20)

\[
Y(s) = G_p(s)U_2(s),
\]

(21)

where \( U_1(s), R(s), Y(s) \) are the Laplace transformation of \( u_1, r \) and \( y \) respectively.

The signal \( u_1 \) will serve as the actuating signal of the ON/OFF controller and will be compared with the threshold value \( V_r \) of ON/OFF controller, which can be tuned. This ON/OFF controller corresponds to two values, 1 and 0. When \( u_1 \) is equal to or bigger than the threshold value, output of ON/OFF control, \( u_2 \), is 1. While \( u_1 \) is smaller than the threshold value, output of ON/OFF control, \( u_2 \), is 0. The two values, 1 and 0, correspond...
to the relay’s status, on and off. They can be described as Figure 9:

![Flowchart showing the relationship between the relay status and ON/OFF control.](Image)

Figure 9. Relationship between relay status and ON/OFF control.

In figure 9, the threshold was selected carefully to connect PID control and ON/OFF control. Then after controlled by hybrid PID-ON/OFF control, the following relationship comes.

\[
Y(s) = U_2(s)G_p(s) \tag{22}
\]

2.2.5 Disturbance Observer (DOB)

Traditionally, observers are mostly discussed with a dynamic system described in state space and so observers are called state observers totally. A state observer estimates the state variables based on the measurements of the output and control variables. [14]

Consider the system defined by

\[
\dot{x} = Ax + Bu \tag{23}
\]

\[
y =Cx \tag{24}
\]

To observer all state variables of the system, regardless of whether some state variables are available for direct measurement; a full-order observer has the following generic form,
\[ \dot{x} = \tilde{A}x + Ky + Hu, \quad (25) \]

where the dimension of state \( x \) of the observer is equal to the dimension of process state \( x \).

The matrices \( \tilde{A} \), \( K \), and \( H \) appearing in the above equation should be chosen to conform with the required property of an observer that the observer state must converge to the process state independent of the state \( x \) and the input \( u \).

To determine these matrices, let \( e := x - \tilde{x} \) be the estimation error. From the three equations above, we have the following derivation:

\[
\dot{e} = Ax + Bu - \tilde{A}(x - e) - KCx - Hu \\
= \tilde{A}e + (-\tilde{A} + A - KC)x + (B - H)u \quad (26)
\]

From this equation, it is seen that for the error to converge to zero, independent of \( x \) and \( u \), the following conditions must be satisfied:

\[
\tilde{A} = A - KC \quad (27)
\]
\[
H = B \quad (28)
\]

When these conditions are satisfied, the estimation error is governed by \( \dot{e} = \tilde{A}e \), which converges to zero if \( \tilde{A} \) is a "stability matrix". To be more obvious and clearer, the following expression can be used:

\[
\dot{x} = Ax + Bu + K(y - \tilde{C}x) \quad (29)
\]

Figure 10 presents a block diagram of this equation, where \( A, B \) and \( C \) are defined by the system plant, \( y \) is the system output, the only freedom in the design of observer is to selection of the gain matrix \( K \).
Given a quantity $\hat{r}$ called the residual, $\hat{r} = y - C\bar{x} = y - \bar{y}$, it represents the difference between the actual observation $y$ and the "synthesized" observation $\bar{y} = C\bar{x}$, produced by the observer. The observer servers as a feedback system designed to derive the residual to zero; as the residual is driven to zero, the input to the above equation due to the residual vanishes and the state of this equation looks like the state of the original process.

![Block diagram of full-order observer for a linear process.](image)

**Figure 10.** Block diagram of full-order observer for a linear process.

Based on the theory of state observer, disturbance observer has been developed. For simplification, system plant can be also described by transfer function in the design of an observer. Unmeasured disturbance or disturbance hard to measure will be observed like the state variable in state space. Figure 11 presents an observer used to observe the unmeasured disturbance.
In Figure 11, the part with dash line around shows a disturbance observer loop. Signals $u$, $d$, $n$ and $y$ are the command, disturbance, noise, and output respectively.

Signal $\hat{d}$ and $\hat{d}_f$ are the disturbance estimated before and after being filtered by the low-pass filter $Q$. The command $u$ is provided by an outer loop controller. As in Figure 11, command $u$ is the direct output of controller. Symbol $G_p$ represents the actual plant and $G_n$ represents 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 $u_{obs}$.

The filtered signal $\hat{d}_f$ from the disturbance observer input and the noise input is determined only by the plant dynamics $G_p$ 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: [21]

$$G_n = \frac{1}{a_p s^n + a_1 s^{n-1} + \cdots + a_{m-1} s + a_m} \quad (30)$$

For designing the observer by Gopinach’s method, the disturbance model is usually given by $d = \frac{1}{s_k}$, then, $Q$ is given by:

$$G(s) = \frac{g_{m+1} s^{k-1} + \cdots + g_{m+2} s + g_{m+1}}{s^{m+1} + g_1 s^{m+2} + \cdots + g_{m+k-2} s + g_{m+k-1}} \quad (31)$$

Generally, the low order disturbance model is employed, that is $k$ selected as $k = 1$. If high order disturbance observer is to be researched, then $k$ should be chosen from the values of $k > 1$.

2.2.6 Disturbance Observer Based PID-ON/OFF Control

Recently, disturbance observer based robust control algorithm has been reported to compensate modeling uncertainties as well as external disturbance. In this thesis, disturbance observer is used with the above researched hybrid PID-ON/OFF control.

Figure 12 shows the block diagram of this complete disturbance observer based control system. The controller is the specified hybrid PID-ON/OFF control. In this thesis, the research of controller and disturbance observer is focused on single-input-single-output systems. The plant models are represented by their corresponding transfer function, and then disturbance is considered as one variable to design the disturbance observer for each single-output-single-output system.
In this thesis, the controlled process is focused on heating, and then the nominal plant model $G_n$ is chosen as a low order approximation of the actual plant. For the single input single output process of a temperature control system, the average rate, $k$, of the temperature increasing process is employed as the value of the nominal plant. [21][28] Then the inverse of the value becomes the gain of the $G_n^{-1}$ in Figure 12.

![Block diagram of disturbance observer based control system.](image)

**Figure 12.** Block diagram of disturbance observer based control system.

\[
G_n \approx G_p
\]

\[
G_n^{-1} = \frac{1}{k}
\]

\[
y \approx (d + u_{obs})k
\]

\[
y \approx \frac{y}{k} - u_{obs}
\]
So, $\dot{d} \approx d$ \hspace{1cm} (36)

The variable $u(s)$ is the controlled signal, $g_c(s)$ is the description of the controller, and $y_f(s)$ is the filtered output temperature. Their relationship is as the following equation:

$$u(s) = [r(s) - y_f(s)]g_c(s) \hspace{1cm} (37)$$

Filter $Q$ is designed to trade-off disturbance and parameter rejection against noise and stability robustness. The disturbance observer in this project is also characterized by the filter $Q$, which is selected as constant $1$ ($\dot{d}_f = \dot{d}$) because this controlled system is a low frequency system. And therefore, the DO system can be realized as the nominal plant.

Besides the filter $Q$ that works for the observer, $F$ is the other filter that works for the feedback signal. In this project, the feedback signal is output temperatures, which are read by thermocouple, and then $F$ is to be realized by one arithmetic average scheme, the numeric average of every several neighborhood output temperature readings. This method for filtering occasionally happening signals is easy to perform by a cycle loop in general control software.

In 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.

In the furnace, the disturbance comes from the short-time (ten to twenty seconds) strait aperture.
CHAPTER 3

RESULTS AND DISCUSSION

3.1 Simulation Results of Thermal Process under Current Control Scheme

To test the performance of the different control schemes, including the current band control, the proposed PID-ON/OFF control as well as DOB based PID-ON/OFF control in ideal condition. The quick and high efficient simulation method is used a lot in this study.

3.1.1 Simulation Results of Thermal Process of TC-1 under Current Control Scheme

The thermal process of each zone of TC-1 loop using band control scheme is simulated by the method introduced in chapter 2 and simulation programs were made with MATLAB software.

a. Zone1.

The simulation results on thermal process of zone 1 under existing band control are shown in Figure 13 (13.a, 13.b, 13.c, 13.d). The temperature development for this condition is very regularly. From 0°C, which is the starting point of all the simulation in this thesis, it increases to setting point and then vibrates in the band area. From 13.b, the vibration range is close to the given range. From 13.c and 13.d, the rise time for the heating zone 1 under this condition is 14600s, the peak time is 15010s, peak temperature
is 205.1 °C and maximum percent overshoot is 2.55%. The average heating rate during the temperature increasing process is 49.29 °C/hr. However, in the temperature maintenance stage, the temperature keeps vibrating regularly long time in such a range, which is not we want.

Figure 13. Thermal process of zone 1 with band control (13.a, 13.b, 13.c, 13.d).

b. Zone 2
The simulation results on thermal process of zone 2 under existing band control are shown in Figure 14 (14.a, 14.b, 14.c, 14.d). The temperature development of zone 2 for this condition is very similar to that of zone 1. From 14.c and 14.d, the rise time for zone 2 under this condition is 15480s, the peak time is 15980s, peak temperature is 205.2 °C and the stable trough temperature is 194.8°C. So the average heating rate during the temperature increasing process is 46.51°C/hr and maximum percent overshoot is 2.6%. However, in the temperature maintenance stage, the temperature keeps vibrating regularly long time in such a range, which is not we want.

Figure 14. Thermal process of zone 2 with band control (14.a, 14.b, 14.c, 14.d).

c. Zone 3.1
Figure 15. Thermal process of zone 3.1 with band control (15.a, 15.b, 15.c, 15.d).

The simulation results on thermal process of zone 3.1 under existing band control are shown in Figure 15 (15.a, 15.b, 15.c, 15.d). The temperature development for this condition is very regularly. From 0°C, which is the starting point of all the simulation in this thesis, it increases to setting point and then vibrates in the band area. From 15.b,
however, the vibration range is bigger than the given range. From 15.c and 15.d, the rise
time for the heating zone 1 under this condition is 14390s, the peak time is 14810s, and
peak temperature is 205.4 °C. The average heating rate during the temperature increasing
process is 50.03 °C/hr and maximum percent overshoot is 2.7%. However, in the
temperature maintenance stage, the temperature keeps vibrating regularly long time in
such a range and vibration range is bigger than the given band, which are not we want.

d. Zone 3.2

Figure 16. Thermal process of zone 3.2 with band control (16.a, 16.b, 16.c).

The simulation results on thermal process of zone 3.2 under existing band control are
shown in Figure 16 (16.a, 16.b, 16.c). The temperature development of zone 3.2 for this condition is very close to that of zone 3.1. From 0°C, temperature increases to setting point and then vibrates in the band area. From 16.b, however, the vibration range is bigger than the given range. From 16.c, the rise time for the heating zone 3.2 under this condition is 14430s, the peak time is 14830s, and peak temperature is 205.3 °C. The average heating rate during the temperature increasing process is 49.89 °C/hr and maximum percent overshoot is 2.65%. However, in the temperature maintenance stage, the temperature keeps vibrating regularly long time in such a range and vibration range is bigger than the given band, which are not we want.

c. Zone 4

The simulation results on thermal process of zone 4 under existing band control are shown in Figure 17 (17.a, 17.b, 17.c). From 0°C, temperature increases to setting point and then vibrates in the band area. From 17.b, however, the vibration range is a little bigger than the given range in the early temperature maintenance stage. From 17.c and 17.d, the rise time for the heating zone 1 under this condition is 46250s, the peak time is 48320s, and peak temperature is 205°C. The average heating rate during the temperature increasing process is 15.57 °C/hr and maximum percent overshoot is 2.5%. At this average heating rate, it will take about 12.8 hrs to reach the setting point, which is too slow for the UNLV research requirement. Besides, in the temperature maintenance stage, the temperature keeps vibrating regularly long time in such a range and vibration range is bigger than the given band, which are not we want, either.
f. Zone 5

The simulation results on thermal process of zone 5 under existing band control are shown in Figure 18 (18.a, 18.b, 18.c, 18.d). The temperature development of zone 5 for this condition is very close to that of zone 1 and zone 2. From 0°C, temperature increases
to setting point and then vibrates in the band area. From 18.b, however, the vibration range is close to the given range. From 18.c and 18.d, the rise time for the heating zone 3.2 under this condition is 13710s, the peak time is 14140s, peak temperature is 205.5 °C and the trough temperature is 194.9°C. The average heating rate during the temperature increasing process is 52.51°C/hr and maximum percent overshoot is 2.75%.

Figure 18. Thermal process of zone 5 with band control (18.a, 18.b, 18.c, 18.d).
g. Zone 6

Figure 19. Thermal process of zone 6 with band control (19.a, 19.b, 19.c, 19.d).

The simulation results on thermal process of zone 6 under existing band control are shown in Figure 19 (19.a, 19.b, 19.c, 19.d). From 0°C, temperature increases to setting
point and then vibrates in the band area. From 19.b, however, the vibration range is
bigger to the given range. From 19.c and 19.d, the rise time for the heating zone 6 under
this condition is 14690s, the peak time is 15940s, peak temperature is 210.7 °C and the
trough temperature is 193.2°C. The average heating rate during the temperature
increasing process is 49.01°C/hr and maximum percent overshoot is 5.35%.

Zone 6 as the main target working area, this thermal condition is not good.

h. Zone 7

Figure 20. Thermal process of zone 7 with band control (20.a, 20.b, 20.c, 20.d).
The simulation results on thermal process of zone 7 under existing band control are shown in Figure 20 (20.a, 20.b, 20.c, 20.d). From 20.a and 20.b, temperature increases to setting point and then vibrates in a range a little bigger than the given range. From 20.c and 20.d, the rise time for the heating zone 7 under this condition is 14040s, the peak time is 14440s, peak temperature is 205.2 °C and the trough temperature is 192.6°C. The average heating rate during the temperature increasing process is 51.28°C/hr and maximum percent overshoot is 2.6%.

i. Zone 8

The simulation results on thermal process of zone 8 under existing band control are shown in Figure 21 (21.a, 21.b, 21.c, 21.d). From 21.a and 21.b, temperature increases to setting point and then vibrates regularly in a range bigger than the given range. From 21.c and 21.d, the rise time for the heating zone 8 under this condition is 14580s, the peak time is 14940s, peak temperature is 208.7 °C and the trough temperature is 191.1°C. The average heating rate during the temperature increasing process is 49.38°C/hr and maximum percent overshoot is 4.35%. Such a big vibration range isn't we want.
3.1.2 Simulation Results of Thermal Process of Simulator Furnace using Band Control

Based on the fact that except the thermal control, TC-1 control system involves several controls such as alarm control and pump control, and these later controls are still on designing; therefore the conditions to test these proposed new thermal control schemes in TC-1 are not ready. To complement this, a furnace, as shown in figure 22, will be used to replace an actual TC-1 heating zone.

Actually, the natural thermal attributes of this furnace and some heating zones like zone 8 are similar as the following figure 23. So it can be used to test the proposed control schemes designed in this thesis as well as original band control scheme. The identified model of this furnace is the following equation:

\[
G(s) = \frac{8.025 \times 10^{-3} s + 1.352 \times 10^{-6}}{s^3 + 2.872 \times 10^{-2} s^2 + 3.362 \times 10^{-5} s}
\]
The simulation results on thermal process of simulator under existing band control are

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shown in Figure 24 (24.a, 24.b, 24.c, 24.d, 24.e, 24.f). From 24.a and 24.b, temperature increases to setting point and then vibrates regularly in a range bigger than the given range. From 24.c and 24.d, the rise time for the simulator under this condition is 1170s, the peak time is 1234s, peak temperature is 205.8 °C and the trough temperature is 192.5°C. The average heating rate during the temperature increasing process is 615.38°C/hr and maximum percent overshoot is 0.4%. From the simulation results, it is obvious that band control cannot bring proper in this high speed heating system.
3.2 Simulation Results of Thermal Process using Hybrid PID-ON/OFF Control

The thermal process of each zone of TC-1 loop using the proposed hybrid PID-ON/OFF control scheme introduced in chapter 2 is simulated and simulation programs were made with MATLAB software.

3.2.1 Simulation Results of Thermal Process of TC-1 using PID-ON/OFF Control

a. Zone 1

The simulation results on thermal process of zone 1 under the hybrid PID-ON/OFF control are shown in Figure 25 (25.a, 25.b, 25.c, 25.d). The temperature development for this condition is very good. From 0°C, temperature increases to then setting point and then vibrates subtly around the setting temperature. From 25.c and 25.d, the rise time for the heating zone 1 under this condition is 14600s (4hr3mm), the peak time is 14300s, and peak temperature is only 200.2 °C. The average heating rate during the temperature increasing process is 49.31 °C/hr and maximum percent overshoot is 0.1%.

Figure 24. Thermal process of simulator with band control (24.a-24.f).
When a low-frequency sine thermal signal, $d = 10\sin 0.001t$ is added as disturbance to the simulation system of zone 1, its results shows a little difference as shown in Figure 26. During the time of 30000s, one bump happens, which has a peak value 203°C and takes 2500s to get back to setting point.
Figure 26. Thermal process of zone 1 with disturbance using hybrid PID-ON/OFF control (26.a, 26.b, 26.c).

b. Zone 2

The simulation results on thermal process of zone 2 under the hybrid PID-ON/OFF...
control are shown in Figure 27 (27.a, 27.b, 27.c, 27.d). The temperature development for this condition is very good. From 0°C, temperature increases to setting point and then vibrates once and then almost converges to the setting temperature. From 27.c and 27.d, the rise time for the heating zone 2 under this condition is 15480s, the peak time is 15520s, and peak temperature is only 200.3 °C. The average heating rate during the temperature increasing process is 46.51 °C/hr and maximum percent overshoot is 0.15%.

When a low-frequency sine thermal signal, $d=10\sin0.001t$ is added as thermal disturbance to the simulation system of zone 2, its results shows little difference with those that without disturbance. As shown in 28.a and 28.b, the temperature developments are very close to the setting point and within the time 28000s, just a small bump happens. Figure 28.c shows the bump peak point and its neighboring setting points.
Figure 27. Thermal process of zone 2 with hybrid PID-ON/OFF control (27.a-27.d).

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Figure 28. Thermal process of zone 2 with disturbance using hybrid PID-ON/OFF control (28.a, 28.b, 28.c).

c. Zone 3.1
Figure 29. Thermal process of zone 3.1 with hybrid PID-ON/OFF control with disturbance (27.a-29.d).

The simulation results on thermal process of zone 3.1 under the hybrid PID-ON/OFF control are shown in Figure 29 (29.a, 29.b, 29.c, 29.d). The temperature development for this condition is very good. From 0°C, temperature increases to setting point and then vibrates once and then almost converges to the setting temperature. From 29.c and 29.d, the rise time for the heating zone 3.1 under this condition is 14390s, the peak time is 14430s, and peak temperature is only 200.3 °C. The average heating rate during the temperature increasing process is 50.03°C/hr and maximum percent overshoot is 0.15%.

When a low-frequency sine thermal signal, \( d = 10 \sin 0.001t \) is added as thermal disturbance to the simulation system of zone 3.1, its results shows little difference with those that without disturbance. As shown in 30.a and 30.b, the temperature developments are very close.
d. Zone 3.2

The simulation results on thermal process of zone 3.2 under the hybrid PID-ON/OFF control are shown in Figure 31 (31.a, 31.b, 31.c, 31.d). The temperature development for this condition is very good. From 0°C, temperature increases to setting point and then vibrates once and then almost converges to the setting temperature. From 31.c and 31.d, the rise time for the heating zone 3.2 under this condition is 14420s, the peak time is 14460s, and peak temperature is only 200.3 °C. The average heating rate during the temperature increasing process is 49.93°C/hr and maximum percent overshoot is 0.15%.
When a low-frequency sine thermal signal, \( d = 10 \sin 0.001t \) is added as thermal disturbance to the simulation system of zone 3.2, its results shows little difference with those without disturbance. As shown in 32.b and 32.b, the temperature developments are very close.
e. Zone 4

The simulation results on thermal process of zone 4 under the hybrid PID-ON/OFF control are shown in Figure 33 (33.a, 33.b, 33.c, 33.d). From 0°C, temperature increases to setting point and then converges quickly to the setting temperature. From 33.c and 33.d, the rise time for the heating zone 4 under this condition is 46260s. The average heating rate during the temperature increasing process is 15.56°C/hr. The overshoot happens in the zone 4 under this control scheme is ignorable.
Figure 33. Thermal process of zone 4 with hybrid PID-ON/OFF control (33.a-33.d).

When a low-frequency sine thermal signal, $d = 10 \sin 0.001t$ is added as disturbance to the simulation system of zone 4, its results show a little difference as shown in Figure 34 (34.a, 32.4, 34.c). During the time of 230000s, one bump happens, which has a peak temperature of 209.8 °C and takes 34600s to get back to the setting point again.
Figure 34. Thermal process of zone 4 with hybrid PID-ON/OFF control with disturbance (34.a, 34.b, 34.c).

f. Zone 5

The simulation results on thermal process of zone 5 under the hybrid PID-ON/OFF control are shown in Figure 35 (35.a, 35.b, 35.c, 35.d). From 0°C, temperature increases to setting point and then it vibrates regularly in a small range around the setting.
temperature. From 35.c and 35.d, the rise time for the heating zone 5 under this condition is 13720s. The peak time is 13780s and the peak temperature is 200.3°C. The average heating rate during the temperature increasing process is 52.47°C/hr. The maximum percent overshoot is 0.15%.

Figure 35. Thermal process of zone 5 with hybrid PID-ON/OFF control with disturbance (35.a-35.d).
When a low-frequency sine thermal signal, $d = 10 \sin 0.001t$ is added as disturbance to the simulation system of zone 5, its results show difference with that in Figure 36 (36.a, 36.b, 36.c). The temperature just converge to some range, however, there are small bumps happening. From 36.c, the bump happens have peak temperature of about 201.9 °C and each takes about 1800s to get back to the setting point again.

Figure 36. Thermal process of zone 5 with disturbance using hybrid PID-ON/OFF control (36.a, 36.b, 36.c).
g. Zone 6

The simulation results on thermal process of zone 6 under the hybrid PID-ON/OFF control are shown in Figure 37 (37.a, 37.b, 37.c, 37.d). From 0°C, temperature increases to setting point and then it have an overshoot. After vibrates twice, it stays close to the setting temperature.

Figure 37. Thermal process of zone 6 with hybrid PID-ON/OFF control (37.a-37.d).
From 37.c and 37.d, the rise time for the heating zone 6 under this condition is 14690s. The peak time is 15600s and the peak temperature is 205.3°C. The lowest trough temperature is 198.3 °C. After the time of 20000s, the temperatures almost keep in the horizontal line. The average heating rate during the temperature increasing process is 49.01°C/hr. The maximum percent overshoot is 2.65%.

Figure 38. Thermal process of zone 6 with disturbance using hybrid PID-ON/OFF control (38.a, 38.b, 38.c).
When a low-frequency sine thermal signal, $d = 10 \sin 0.001t$ is added as disturbance to the simulation system of zone 6, difference from the one without disturbance appears as the shown results in Figure 38 (38.a, 38.b, 38.c). From 38.e, the peak temperature is 211.7 °C. Later on there are regular bumps happening, which have peak temperature of 205 °C and each takes about 3240s to get back to the setting point again.

h. Zone 7

The simulation results on thermal process of zone 7 under the hybrid PID-ON/OFF control are shown in Figure 39 (39.a, 39.b, 39.c, 39.d). From 0°C, temperature increases to setting point and then it stays close to the setting point. From 39.c and 39.d, the rise time for the heating zone 7 under this condition is 14040s. The peak time is 14070s and the peak temperature is 200.2°C. The lowest trough temperature is 198.3 °C. After the time of 20000s, the temperatures almost keep in the horizontal line. The average heating rate during the temperature increasing process is 51.28°C/hr. The maximum percent overshoot is 0.1%.

(39.a)   (39.b)
When a low-frequency sine thermal signal, $d = 10 \sin 0.001t$ is added as disturbance to the simulation system of zone 7, difference from the one without disturbance is not obvious. The thermal process of zone 7 with a low external frequency disturbance using PID-ON/OFF control is shown as figure 40.

Figure 39. Thermal process of zone 7 with hybrid PID-ON/OFF control (39.a-39.d)

Figure 40. Thermal process of zone 7 with disturbance using hybrid PID-ON/OFF control.
i. Zone 8

Figure 41. Thermal process of zone 8 with disturbance using hybrid PID-ON/OFF control (41.a-41.d).

The simulation results on thermal process of zone 8 under the hybrid PID-ON/OFF

66

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control are shown in Figure 41 (41.a, 41.b, 41.c, 41.d). From 0°C, temperature increases to setting point and then it have an overshoot. After vibrates twice, it stays close to the setting temperature. From 41.c and 41.d, the rise time for the heating zone 8 under this condition is 14590s. The peak time is 15120s and the peak temperature is 203.2°C. The lowest trough temperature is 197.7 °C. The average heating rate during the temperature increasing process is 49.35°C/hr. The maximum percent overshoot is 1.6%.

When a low-frequency sine thermal signal, \( d = 10\sin 0.001t \) is added as disturbance to the simulation system of zone 8, difference from the one without disturbance appears as the shown results in Figure 42 (42.a, 42.b, 42.c). From 42.c, there are regular bumps happening, which have peak temperature of 204 °C and each takes about 1990s to get back to the setting point again.
Figure 42. Thermal process of zone 8 with hybrid PID-ON/OFF control with disturbance (42.a, 42.b, 42.c).

3.2.2 Simulation Results of Thermal Process of Simulator Furnace using Hybrid PID-ON/OFF Control Scheme

The simulator has a big heating rate, which is also obvious in this simulation. The simulation results of thermal process of simulator using hybrid PID-ON/OFF control are shown in Figure 43. From 43.c and 43.d, the rise time and peak time of this simulator under this condition are 1170s and 1188s respectively. The average heating rate of the temperature increasing process is 615°C/hr and maximum percent overshoot is 0.5%. Neither big overshoot nor bumps happen in the thermal process.

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Figure 43. Thermal process of simulator with hybrid PID-ON/OFF control (43.a-43.d).

With a low-frequency sine thermal signal, \( d = 10 \sin 0.001t \), added as disturbance to the simulation system of simulator, difference from the one without disturbance appears, as the shown results in Figure 44 (44.a, 44.b, 44.c). From 44.c, there are bumps.
happening. During the process until 30000s, there are two bumps, first of which has a peak temperature as 205 °C and takes about 3000s to get back to the setting point again. The second one is more serious than the first one.

Figure 44. Thermal process of simulator with disturbance using hybrid PID-ON/OFF control (44.a, 44.b, 44.c).
3.3 Simulation Results of Thermal Process under DOB Based PID-ON/OFF Control

From Section 3.2, zone 1, zone 2, zone 3.1, zone 3.2 and zone 7 got good results under the hybrid PID-ON/OFF control. However, the other zones as zone 4, zone 5, zone 6 and zone 8, still were affected inversely by the disturbance even using the hybrid PID-ON/OFF control. This is reasoned by these zones' specialties in the circulation loop. Here Simulation for these affected zones with disturbance observer based PID-On/OFF control will be done as following.

3.3.1 Simulation Results of Thermal Process of TC-1 using DOB based PID-ON/OFF Control

a. zone 4

Under this disturbance observer (DOB) based control, the simulation results of zone 4 are shown in figure 45 (45.a, 45.b, 45.c). From 45.c, zone 4 takes 24800s to reach the setting temperature for the first time. So the average heating rate of the temperature increasing process is 29.03 °C/hr. From the following figure, the peak temperature is very close to the setting temperature, and the peak time is very close to the rise time as well as the settle time, too. In the temperature maintenance process, the temperatures stay closely to the setting point.
Figure 45. Thermal process of zone 4 with disturbance using hybrid PID-ON/OFF control (45.a, 45.b, 45.c).

b. zone 5

In the heating process of zone 5 under disturbance based PID control, from figure 46, the rise time is 13760s, the peak time is 13930s, peak temperature is 200.3°C, and lowest temperature is 199.6 °C. So the average heating rate is in temperature increasing stage is 52.32 °C/hr and the maximum percent overshoot is 0.15%.
Figure 46. Thermal process of zone 5 with disturbance using DOB Based hybrid PID-ON/OFF control (46.a-46.d).

c. zone 6

In the heating process of zone 6 under disturbance based PID control, from figure 47, the rise time of zone 6 is 14390s, the peak time is 14750s, peak temperature is 202.1°C,
and lowest temperature is 197.5 °C. So the average heating rate in temperature increasing stage is 50.03 °C/hr and the maximum percent overshoot is 1.05%.

Figure 47. Thermal process of zone 6 with disturbance using DOB Based Hybrid PID-ON/OFF Control (47a-47.d).
d. zone 8

Figure 48. Thermal process of zone 8 with disturbance using DOB based hybrid PID-ON/OFF control (46.a, 46.b, 46.c, 46.d).

The simulation results of zone 8 with DOB based PID-ON/OFF control are shown in
figure 48 (48.a, 48.b, 48.c, 48.d). From 48.c and 48.d, the rise time is 14560s, the peak time is 15110s, peak temperature is 203.3 °C, and lowest temperature is 197.8 °C. So the average heating rate in temperature increasing stage is 49.45 °C/hr and the maximum percent overshoot is 1.65%.

3.3.2 Simulation Results of Thermal Process of Simulator Furnace using DOB based Hybrid PID-ON/OFF Control Scheme

A sine thermal signal $d = 10 \sin 0.001t$ is used as disturbance to the system. When observer based PID-ON/OFF control is used, the result come out as in Figure 49. The rise time is 1170s, the peak time is 1186s, peak temperature is 201 °C, the trough time is 1234s and trough temperature is 198.8 °C. So the average heating rate is 615.38 °C/hr. The maximum percent overshoot is 0.5%. The temperature maintenance is very stable and converges to a very small range.
Figure 49. Thermal process of simulator with disturbance using DOB based hybrid PID-ON/OFF control (49.a-49.d).

3.4 Simulation Results Comparing and Discussion

3.4.1 Simulation Results Comparing and Discussion of Thermal Process using Band Control and PID-ON/OFF Control

The results of the heating zones as well as the simulator using different control schemes are to be compared as following tables:

For zone 1, the upper part of drainage tank, it has a thermal attribute itself in that it contacts with coolant in a big area before coolant is pressured out to circulation loop. So when ignoring the only vibration specialty from band control, the vibration range and maximum overshoot are both acceptable. When hybrid PID-ON/OFF control is used, the vibration is negligible and other attributes are the similar to the results from the band control. This similar attributes as well difference between band control and PID-
ON/OFF control also happen to zone 2, zone 3.1, zone 3.2 and zone 7.

Table 3. Results of zone 1 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>Zone 1</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>4.06</td>
<td>4.06</td>
</tr>
<tr>
<td>peak time (hour)</td>
<td>4.17</td>
<td>3.92</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>205.1</td>
<td>200.2</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>49.29</td>
<td>49.31</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.55%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[195.0, 205.1]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Table 4. Results on zone 2 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>Zone 2</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>peak time (hour)</td>
<td>4.44</td>
<td>4.31</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>205.2</td>
<td>200.3</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>46.51</td>
<td>46.51</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.6%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[194.8, 205.2]</td>
<td>negligible</td>
</tr>
</tbody>
</table>
Table 5. Results of zone 3.1 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>Zone 3.1</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>3.99</td>
<td>3.99</td>
</tr>
<tr>
<td>peak time (hour)</td>
<td>4.11</td>
<td>4.01</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>205.4</td>
<td>200.3</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>50.03</td>
<td>50.03</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.7%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[192.5, 205.4]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Table 6. Results of zone 3.2 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>Zone 3.2</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>4.01</td>
<td>4.01</td>
</tr>
<tr>
<td>peak time (hour)</td>
<td>4.12</td>
<td>4.02</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>205.3</td>
<td>200.3</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>49.89</td>
<td>49.93</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.65%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[193.4, 205.3]</td>
<td>negligible</td>
</tr>
</tbody>
</table>
Table 7. Results of zone 4 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th></th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>12.85</td>
<td>12.85</td>
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<tr>
<td>peak time (hour)</td>
<td>13.42</td>
<td>13.42</td>
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<tr>
<td>Peak temperature (°C)</td>
<td>205</td>
<td>200.1</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>15.57</td>
<td>15.56</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.5%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[193.3, 205.0]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Table 8. Results of zone 5 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th></th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>3.80</td>
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<td>peak time (hour)</td>
<td>3.93</td>
<td>3.83</td>
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<tr>
<td>Peak temperature (°C)</td>
<td>205.5</td>
<td>200.3</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>52.51</td>
<td>52.47</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.75%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[194.9, 205.5]</td>
<td>negligible</td>
</tr>
</tbody>
</table>
Table 9. Results of zone 6 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>Zone 6</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>4.08</td>
<td>4.08</td>
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<tr>
<td>peak time (hour)</td>
<td>4.43</td>
<td>4.33</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>210.7</td>
<td>205.3</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>49.01</td>
<td>49.01</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>5.35%</td>
<td>2.65%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[193.2, 210.7]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Table 10. Results of zone 7 using band control and PID-ON/OFF control

<table>
<thead>
<tr>
<th>Zone 7</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>3.90</td>
<td>3.90</td>
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<tr>
<td>peak time (hour)</td>
<td>4.01</td>
<td>3.91</td>
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<tr>
<td>Peak temperature (°C)</td>
<td>205.2</td>
<td>200.2</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>51.28</td>
<td>51.28</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.6%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[192.6, 205.2]</td>
<td>negligible</td>
</tr>
</tbody>
</table>
Table 11. Results of zone 8 using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>Zone 8</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>4.05</td>
<td>4.05</td>
</tr>
<tr>
<td>peak time (hour)</td>
<td>4.15</td>
<td>4.20</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>208.7</td>
<td>203.2</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>49.38</td>
<td>49.35</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>4.35%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[191.1, 208.7]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Table 12. Results of furnace using band control and PID-ON/OFF control.

<table>
<thead>
<tr>
<th>simulator</th>
<th>Band control</th>
<th>PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>rise time (hour)</td>
<td>0.325</td>
<td>0.325</td>
</tr>
<tr>
<td>peak time (hour)</td>
<td>0.343</td>
<td>0.33</td>
</tr>
<tr>
<td>Peak temperature (°C)</td>
<td>205.8</td>
<td>201.0</td>
</tr>
<tr>
<td>Average heating rate (°C/hr)</td>
<td>615.38</td>
<td>615.38</td>
</tr>
<tr>
<td>maximum percent overshoot</td>
<td>2.9%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Vibration range (°C) for long time</td>
<td>[192.5, 205.8]</td>
<td>negligible</td>
</tr>
</tbody>
</table>

From table 3-12, whether system has a high or low average heating rate, it has a vibration range bigger than the given band width when using band temperature control. Besides, in the temperature maintenance stage, the temperatures vibrate almost infinitely.
in this range. These results are too crude and don’t meet the requirements of TC-1 circulation loop. These problems come from the crudity of band control scheme itself. This phenomenon happens to all the nine heating zones as well to the simulator.

Table 13. Attributes comparing between PID-ON/OFF control and DOB based PID-ON/OFF control on zones with disturbance.

<table>
<thead>
<tr>
<th>Zone and furnace with disturbance</th>
<th>Different from conditions with disturbance using PID-ON/OFF control</th>
<th>Different from condition with disturbance using DOB based PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 subtle</td>
<td>No simulation</td>
<td></td>
</tr>
<tr>
<td>Zone 2 subtle</td>
<td>No simulation</td>
<td></td>
</tr>
<tr>
<td>Zone 3.1 subtle</td>
<td>No simulation</td>
<td></td>
</tr>
<tr>
<td>Zone 3.2 subtle</td>
<td>No simulation</td>
<td></td>
</tr>
<tr>
<td>Zone 4 limited bumps</td>
<td>Bumps disappear</td>
<td></td>
</tr>
<tr>
<td>Zone 5 limited bumps</td>
<td>Bumps disappear</td>
<td></td>
</tr>
<tr>
<td>Zone 6 limited bumps</td>
<td>Bumps disappear</td>
<td></td>
</tr>
<tr>
<td>Zone 7 subtle</td>
<td>No simulation</td>
<td></td>
</tr>
<tr>
<td>Zone 8 limited bumps</td>
<td>Bumps disappear</td>
<td></td>
</tr>
<tr>
<td>Furnace Limited bumps</td>
<td>Bumps disappear</td>
<td></td>
</tr>
</tbody>
</table>

However, when the optimization control scheme, the hybrid PID-ON/OFF control, is used, all these problems are almost solved. Under the hybrid PID-ON/OFF control, none
of these heating zones or the simulator has a maximum percent overshoot bigger than 2%. Moreover, under this control scheme, all the vibration range in the temperature maintenance is ignorable.

3.4.2 Simulation Results Comparing and Discussion of Thermal Process with Disturbance using PID-ON/OFF Control and DOB based Control

Simulation for DOB based PID-ON/OFF control was done on zone 4, zone 5, zone 6, zone 8 and simulator furnace. From table 14, the rise time is shortened greatly when DOB is used. This can be reasoned by the low efficiency of the MHD-pump. Moreover, when DOB is used, the inverse affection from low frequency external disturbance is negligible, where no bump happens.

Table 14. Results comparing between PID-ON/OFF control and DOB based PID-ON/OFF control on zones with disturbance.

<table>
<thead>
<tr>
<th>Zone and furnace with disturbance</th>
<th>PID-ON/OFF control</th>
<th>DOB based PID-ON/OFF control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 4</td>
<td>Rise time: 46260</td>
<td>Rise time: 24800s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bumps disappear</td>
</tr>
<tr>
<td></td>
<td>Bump peak</td>
<td></td>
</tr>
<tr>
<td></td>
<td>temperature: 209.8°C</td>
<td></td>
</tr>
<tr>
<td>Zone 5</td>
<td>Bump peak</td>
<td>Bumps disappear</td>
</tr>
<tr>
<td></td>
<td>temperature: 209.8°C</td>
<td></td>
</tr>
<tr>
<td>Zone 6</td>
<td>Bump peak</td>
<td>Bumps disappear</td>
</tr>
<tr>
<td></td>
<td>temperature: 211.7°C</td>
<td></td>
</tr>
<tr>
<td>Zone 8</td>
<td>Bump peak</td>
<td>Bumps disappear</td>
</tr>
<tr>
<td></td>
<td>temperature: 209.8°C</td>
<td></td>
</tr>
<tr>
<td>Furnace</td>
<td>Bump peak</td>
<td>Bumps disappear</td>
</tr>
<tr>
<td></td>
<td>temperature: 210.3°C</td>
<td></td>
</tr>
</tbody>
</table>
3.5 Experimental Results and Discussion of Thermal Process on Simulator Furnace with Different Control Schemes

3.5.1 Experimental Results and Discussion of Thermal Process of Simulator Furnace using Band Control

The furnace with similar thermal characteristic of a heating zone of TC-1 is employed as the simulator to test different control schemes researched in this thesis. The furnace transfer function was identified in the earlier stage of this thesis.

The simulator is controlled by a standard solid state relay in one small control box, which is connected via cable to the Data Acquisition system from National Instrument Inc. The PID control algorithm and the disturbance observer based PID control algorithm are achieved by using LabVIEW programs.

In TC-1 system, all heaters are only ON/OFF controlled using solid state relays, which get control signals from a computer. There is not any interim value for heater control. In the scheme of serial combination of PID control and ON/OFF control, one interim is employed to serve as the serial interface between the PID control output and ON/OFF input. This interim can be obtained with the Pulse Width Modulation (PWM) (Sandler 1993). However, the too much frequent ON and OFF switch 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, or called by the ON/OFF input, to 0 if output is less than it, and round toward 1 if PID output is bigger than the medium value.

To get the general performance of the band control in heating process, experiments
were conducted on the simulator with the band temperature control scheme. Figure 50 shows the results from the simulator under this control scheme. Furnace is heated from room temperature. The two lines correspond to the two band limit temperature values. And Figure 51 is a local zoom figure to this thermal process.

Figure 50. Experimental thermal process of furnace using band control (a).

From Figure 51, simulator furnace comes to about 198.47 °C at 960s then its temperature decreases, vibrate around temperature 195 °C once, and then the it vibrate once around a bigger value 197 °C. The average heating rate in the initial heating process is about 631.76 °C/hr. During the temperature maintenance process, it vibrates regularly about setting point in a range from 191 °C to 207 °C, which is bigger than the supposed range from 195 °C to 205 °C. The average vibration period is 390s. Under this control scheme, temperature vibrates for long time.
3.5.2 Experimental Results and Discussion on Thermal Process of Simulator Furnace using Hybrid PID-ON/OFF Control

Experiments were conducted on the same furnace using a hybrid PID-ON/OFF control scheme under the same environmental conditions as that of experiments for band control scheme. Figure 52 shows the overall thermal process of the simulator furnace with this hybrid PID-OFF control method. Simulator furnace goes to setting temperature, only has a very small overshoot, and then quickly it comes to the stable temperature maintenance process.

Experiments were conducted on the same furnace using a hybrid PID-ON/OFF control scheme under the same environmental conduction as that of experiments for band control scheme. Figure 52 shows the overall thermal process of the simulator furnace with this hybrid PID-OFF control method. Simulator furnace goes to setting temperature, only has a very small overshoot, and then quickly it comes to the stable temperature maintenance process.
maintenance process.

Figure 52. Experimental thermal process of furnace using PID-ON/OFF control (a).

Figure 53. Experimental thermal process of furnace using PID-ON/OFF control (b).

In Figure 53, at time of 1175.73s, furnace comes to the setting temperature for the first time, and at time of 1200.32s, it arrives at the peak temperature 200.64°C, at time of 1265.70s, it decreases to a lowest temperature 198.07°C. Since time of 1343s, it stays in a
very small temperature range. So with this PID-ON/OFF control method, the maximum percent overshoot is only 0.32%. From this figure, at time of 1000s, the temperature is almost 188°C. So from 188°C to the rise time point, the time length is 175.73s

Figure 54. Experimental thermal process of furnace with disturbance using PID-ON/OFF control scheme (a).

In section 3.2, a low frequency mild amplitude sine thermal signal was employed as disturbance to the system; however, it is hard to make such an actual one to this simulator furnace. In this experiment, disturbance is made by opening the door at a fixed position to a small gap for about 0.4 minutes. Figure 54 shows the temperature development process with the disturbance happening.
3.5.3 Experimental Results and Discussion of Thermal Process of Simulator Furnace using Disturbance Observer Based PID-ON/OFF Control Scheme

Figure 55. Experimental thermal process of furnace using DOB based PID-ON/OFF control (a).

Experimental results from the disturbance observer based PID controlled simulator brought a very good heating process. As shown in figure 55, simulator was heated from an approximate temperature, 32°C, to setting point 200°C and then maintained in a small range around the setting temperature. In the local zoom figure as Figure 56, it is clear that the peak temperature is 200.02°C and the lowest temperature is 198.47°C. So the maximum percent over is 0.01%, which is a very great value.

Also in Figure 56, it is clear that during the temperature maintenance process the temperature vibrates subtly just about inside a range of 1°C around the setting temperature.
The same method in section 3.5.2 for disturbance is used again to make a disturbance for about 0.4 minutes. Comparing figure 57 and figure 54, it is obvious that the temperature decreasing more slowly when disturbance observer is used than the one from only hybrid PID-ON/OFF control is used during disturbance happening. After that, it took a shorter time to return the stable temperature maintenance phase. It took DOB based PID-ON/OFF control about 3.8 minutes while took PID-ON/OFF about 4.6 minutes to reach the stable phase. Besides, temperature curve from DOB based control has a smaller overshoot of 0.75% than that from only PID-ON/OFF control, whose overshoot was about 1.25%.

It is obvious the disturbance made in this experiment can not represent the actual disturbance in control systems, because opening door inevitably damages the system to some degree. And this damage to the system correspondingly brings error to the actual
effect of disturbance observer based controller.

Figure 57. Local Experimental thermal process of furnace with disturbance using DOB based PID-ON/OFF control.

However, the performance of hybrid PID-ON/OFF control as well as the difference of control schemes whether disturbance observer is used is illustrated. PID-ON/OFF scheme can control thermal process efficiently and reject external disturbance to some degree. When PID-ON/OFF control is used together with a disturbance observer, the inverse affection from the external disturbance can be rejected further.
CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Based on the theory of band control, PID control and disturbance observer, the thermal process of the nine heating zones in the TC-1 loop as well as of a simulator furnace have been analyzed. Different control schemes have been studied and corresponding experiments were conducted in this thesis. As illustrated by the simulation results and experimental results, several conclusions can be drawn as following:

1. Band control in thermal process works very crudely. Under band temperature control scheme, system temperature vibrates frequently during the temperature maintenance process for long time. Usually, the vibration range is rarely smaller than the given band width even for slow heating process, while in the quick heating system, the vibration range is even much bigger than the given temperature band.

2. PID control method can work efficiently for thermal process when connected to ON/OFF control method. The combination of these two classic control schemes can control the thermal process efficiently whether the system has a quick heating speed or low heating speed. When ignoring external disturbance, the hybrid PID-ON/OFF control makes a precise control result in simulation and even in actual experiments. When
considering system with low frequency disturbance, the hybrid PID-ON/OFF control scheme can be used elementarily in thermal process. Under this hybrid control scheme, the inverse affection from the disturbance in system thermal process can be reduced to some limited degree.

3. Disturbance observer is easy to use together with classic control methods. For systems with low frequency disturbance, disturbance observer based control can bring a good result. In this thesis, disturbance observer based hybrid PID-ON/OFF control was proposed for temperature system with low frequency disturbance. For single input single output system, a nominal model for observer coming from the average rate of system plant works greatly. During the thermal process whether system has a low or high heating speed, when disturbance observer based PID-ON/OFF control is used, the inverse affection from low frequency disturbance almost disappears.

4.2 Recommendations for Future Work

1. Further research the connection between the PID controller and ON/OFF control. More advanced method for signal handing over and taking over rather than just one threshold, which will reduce the error in system command signals. Research on continuous or multiple positions rather than only two-position heater controller connected to PID control is meaning to be done in the future.

2. Further design a disturbance observer based PID-ON/OFF controller for multi-input-multi-output systems. In the actual thermal process of TC-1 loop, the nine zones always work together, so a final multi-input-multi-output disturbance observer based
PID-ON/OFF controller is necessary for this project.

3. Further design a disturbance observer based PID-ON/OFF controller for the cooling process. An advanced cooling scheme is supposed to replace the current natural cooling method of TC-1 control system, which takes a long time, and also the stress from the cooling process is supposed to be further reduced.
REFERENCES


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Thesis Title:
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