



**DESIGN OF MODEL REFERENCE ADAPTIVE CONTROL BASED
TEMPERATURE CONTROL FOR GLASS MELTING FURNACE**

**HAWASSA UNIVERSITY
INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING**

MASTER OF SCIENCE

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**May 2020
Hawassa, Ethiopia**



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TEMPERATURE CONTROL FOR GLASS MELTING FURNACE**

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A Thesis Submitted To

The School of Electrical and Computer Engineering for the Partial Fulfillment of the
Requirements for the Degree of Master of Science in Electrical and Computer Engineering
(Control and Instrumentation Engineering)

By

Mearg Ifewerki Fisaha

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Approval

This is to certify that the thesis entitled “**Design of Model Reference Adaptive Control Based Temperature Control for Glass Melting Furnace**” submitted in partial fulfillment of the requirements for the degree of **Master’s Science** with specialization in **Control and Instrumentation Engineering**. The Graduate Program of the School of Electrical and Computer Engineering, and has been carried out by **Mr. Mearg Ifewerki** (ID. No: **PGCon/028/09**), under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence here by can submit the thesis to the department.

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Declaration

I, the undersigned declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been composed by myself, with the guidance of my advisor.

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Acknowledgment

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Abstract

The glass manufacturing process is a complex and non-linear process. The quality of the final glass product depends on the temperature profile of the molten glass within a glass melting furnace. Inappropriate variations in the molten glass temperature affect the physical properties of the glass. In order to maintain the quality of the product, the temperature of the molten glass in the furnace must be monitored and controlled by a control system. The designing and testing of a controller require an appropriate process model that describes the process dynamics with enough accuracy. The modeling was distributed by applying energy balance using thermodynamic and energy conservation laws and a state-space model was derived from the energy balance equations. The temperature of glass melting is critical for the assembly of glass containers which are produced in continuous glass melt tank furnaces. Raw materials are continuously charged onto the glass melt to make batch blanket. The temperature of the glass melting determines the quantity of glass in the gob which is placed in the mold and thus affects the quality of the finished container. There are frequent temperatures fluctuations in the glass as it exits the main furnace .The aim of this thesis is to design MIT and lyapunov rule based model reference adaptive control for temperature of glass melting furnace. The controller parameters are adjusted automatically using adaptive adjustment mechanism .In this case the error between reference model output and actual output of the glass melting furnace is minimized. The temperature control of glass furnace based on MIT and lyapunov rule is simulated using MATLAB/SMULINK and its performance is compared with conventional PID controller. The simulation has shown that performance of the model reference adaptive control (MRAC) is better than PID controller.

Keyword- Glass melting furnace, temperature control, model reference adaptive control, Lyapunov rule, PID controller.

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Abbreviations

A	Area
\underline{A}	State matrix
A/F	Air fuel ratio
\underline{B}	Control matrix
C	Capacitance
C	Output matrix
c_p	Specific heat
\underline{D}	Noise matrix.
g	Acceleration of gravity
h	Heat transfer coefficient
H	Height
L	Length
LHV	Lower heating value
L	Lyapunov
m	Mass
MIT	Massachusetts Institute of Technology
MRAC	Model Reference Adaptive Control
MW	Molecular weight
PID	Proportional Integral Derivative
P	Pressure
Q	Heat transfer
R	Resistance
R	Gas constant
r	Radius
RU	Universal gas constant
T	Temperature
V	Volume
W	Width
X	Glass Level
x	State vector

ε	Emissivity
ρ	Density
σ	Stephan-Boltzmann constant
e	tracking error
y_p	plant output
y_m	Reference model output
J	loss function
γ	Adaptation gain
G_m	Reference model transfer function
G_p	Plant transfer function
u_c	Control signal
θ_1	plant adaptation parameter
$\%OS$	Maximum Overshoot
t_s	Settling time
δ	Damping ratio
w_n	Natural frequency
k	scaling gain for error

CHAPTER ONE

Introduction

1.1. Background

Glass furnace could be a key subsystem of a glass industry because it is employed for the melting of glass, which is the main task in glass manufacturing. The glass furnace is that place where the molten glass is produced and processed to produce glass products. Depending on the type of glass produced, the same principle but the technology may be varies. A glass furnace is considered as a reactor (a rectangular tank) where the raw materials are burnt in a limited space surrounded by refractory, at high temperatures of 1200 °C – 1300 °C to provide molten glass. The melting area of a glass furnace contains a molten glass bath and a combustion chamber. The melting area is made up of refractory, which is capable of handling high temperatures. Glass furnaces differ mainly by their preheating system of combustion air and by their shapes. The shape of the furnace depends on the type of glass produced. The furnace operation involves combustion, heat transfer, batch melting, etc. [1, 2]. Glass is produced from various raw materials like silica sand, soda ash, limestone, recycled cullet, and other additives [4]. A mixture of these raw materials is known as batch and it's stored and handled by a batch processing system. The batch is fed into the furnace through a continuous feeding system and is heated to create a homogeneous melt of glass. This molten glass is then discharged through the feeders for its further processing like forming and polishing [3-5]. The plant could be a continuously operating tank furnace as shown in Figure 1.1. Feeding within the raw material is complete by two feeders with pusher-type shovels. The rate of feeding depends on the stroke length of the moves determined by the position of an excenter. The feeders are connected to the working tank.

The heat is required to achieve such temperature in the bath. Heat is obtained by fuel or gas combustion within the combustion chamber. The value of melting and operation criticality determines the type of heat source. Fuel flames, directly heat the melt, mainly by heat transfer through radiations. The mass inlet streams are glass raw material, composed of fuel, and

combustion air. The outlet streams are flue gas and molten glass . Normally, a regenerator is employed to recover heat from the flue gases and preheat the combustion air [1].

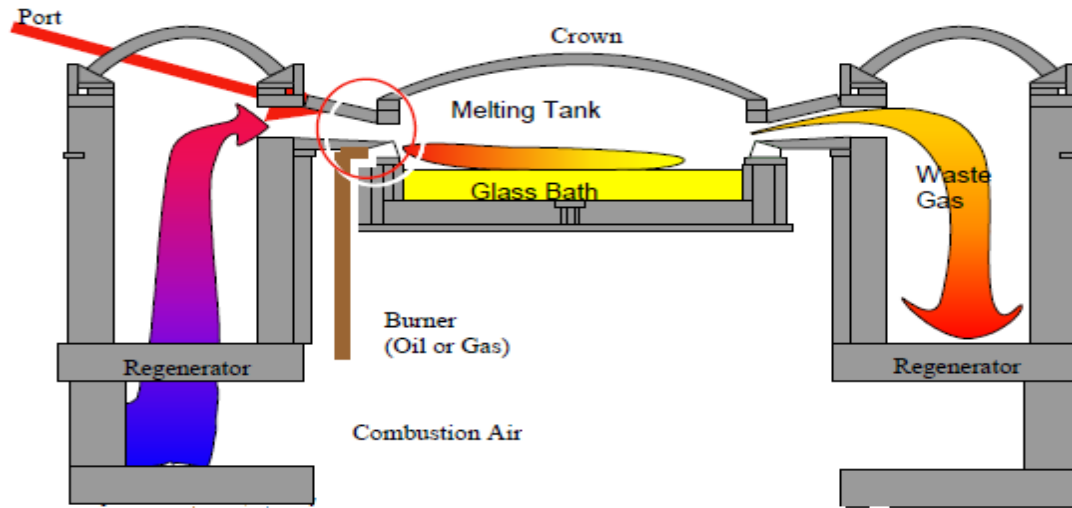


Figure1. 1 lateral view of a side-port regenerative glass [1]

The most important requirement to be met in respect of feeding is to keep the glass level to a constant value. If the furnace pressure is lower or higher than the atmospheric pressure, flames cold air may stream or shoot out from the opening into the furnace. The pressure inside the furnace is kept constant, somewhat above the atmospheric pressure. The temperature of the melted glass affects the chemical reactions going within the glass. The glass melting furnace complex and nonlinear process. So it's still common that glass furnaces are controlled by simple controllers like PID regulators or by manual interventions of furnace operators [6, 7].

In the glass industry, the standard of the ultimate product depends on the quality of the molten glass in the melting furnace. The quality of molten glass, in turn, depends upon the temperature of the molten glass. Thus, in order to maintain the product quality, the temperature of the molten glass in the furnace must be monitored and controlled. The temperature of the molten glass is controlled by adjusting the amount of heat input to the furnace. In order to well control of the glass temperature will be achieved through monitoring and integrated control of the variables [2, 5].

1.2 Problem Statement

Temperature control is main part within the melting glass furnace process and it has an important influence on the quality of the products. Inadequate temperature control in glass manufacturing will result to some product defects. So to effectively control the temperature within the glass furnace, the glass must be heated to a given melting temperature quickly. Additionally, the temperature difference between parts of the glass surface must be very small, i.e., the glass surface must be heated evenly. It's clear that in order to control the glass furnace, a variable process with respective parameters will be designed to reduce the insufficient temperature while sustaining the required output glass temperature. During this work, the adaptive controller is proposed. A control system is a device that regulates or controls the dynamics of temperature glass melting furnace.

1.3 Objective

1.3.1 General Objective

The main objective of this thesis is to design Model Reference Adaptive Control (MRAC) system for a glass melting furnace to improve the quality of the glass and performance of the furnace. The modeling and controlling of the melting furnace are important issues.

1.3.2 Specific Objectives

- ✓ To modify the mathematical model of the glass melting process and its associated equipment.
- ✓ To develop relationships among process variables and improved control Strategies for the glass melting process.
- ✓ To design an MRAC temperature control system for the glass melting furnace.
- ✓ To test and validate the temperature control system using MATLAB.
- ✓ To compare the performance of PID and Model Reference Adaptive Control (MRAC) schemes.

1.4 Scope and Limitation of This Thesis

1.4.1 Scope of this Thesis

This thesis is targeted on the designing based on Lyapunov and MIT model reference adaptive control method for the glass melting furnace. It Includes linearization technique and considers the system only with one input which is fuel flow and one output which is temperature. The effectiveness between MRAC controller and conventional PID controller is studied in terms of maximum overshoot, rise time (t_r) and settling time (t_s). The designed system is finally simulated using Matlab for reference inputs of the controlled variables.

1.4.2 Limitation of The Thesis

In this thesis is not considered, the amount of excess oxygen of the glass melting furnace. Necessity of excess oxygen model parameters identification has not arisen. However, at maximum operating conditions with high energy consumption, the probability of producing undesirable emission may be increase.

1.5 Methodology

The following methodologies have been used for the accomplishment of this thesis:

- The work of this thesis is performed through the series tasks from the identification of the problem up to the final goal through reviewing different literatures.
- In order to meet the above specified objectives of this thesis, the first thing we conducted is literature survey. Which, we reviewed what have been done before this thesis about glass melting furnace.
- Different kinds of literature that are related to this thesis work are reviewed.
- Mathematical modeling of the glass melting furnace is the first step to design the controller. This model is a nonlinear, with one input one output variable. It is necessary to linearize the nonlinear glass melting furnace around suitable operating conditions. Then the nonlinear which have to be linearize using Taylor series linearization technique in

order to implement a controller. After modeling the system based on linearization, plant output is controlled using MRAC based on MIT and Lyapunov adaptation rule .

- The proposed system model is designed and simulated using MATLAB/Simulink.
- Finally, conclusions are given from the simulation result.

1.6 Thesis Outline

This thesis is organized into five chapters including this introduction. The rest of the thesis is organized as follows.

Chapter two: describes the theory and operation principle of a glass furnace. It also introduces the current techniques used in melting control and also technological advancement including Adaptive control, Model Reference Adaptive control, how these techniques have been implemented in different applications, different literature related to temperature and their control system are reviewed.

Chapter three: in this chapter includes the linearization method of the nonlinear mathematical model of the glass melting furnace. The methodology used to develop Model Reference Adaptive control based on MIT rule is also presented. It is in this chapter where MATLAB/Simulink models for Model Reference Adaptive Control and Model Reference Adaptive System are presented.

Chapter four: presents the simulation results and details the results obtained through simulation of the proposed Model Reference Adaptive control system design for melting parameter control, the analysis and comparisons of these results with the results of the conventional PID and MRAC controllers.

Chapter five: draws the conclusion from the work done in this thesis and recommend further research possible in this area.

CHAPTER TWO

Literature Review

2.1 Overview

This chapter will cover the theoretical overview of furnace operation, and conventional control theory schemes like the PID controller and adaptive control system. Moreover, different articles and journals are reviewed which has been done so far related to glass melting furnace.

2.2 Generalized View of Furnace Operation

2.2.1 Glass Melting

Before glass will be used for a particular purpose, a glass product has got to be manufactured. This section describes some relevant glass manufacturing processes. glass manufacturing more focused up on Energy consumption which represents a big portion of the total glass production. The glass melting tank is where the process starts with raw material, and cullet fed into a furnace for melting. Furnaces can use fossil fuels or electricity for the heating process. In this thesis, fossil fuel is assumed to be employed as an input to the furnace for the heating process, since it's a cost-effective relatively. Better monitoring of the glass temperature can aid ensure product uniformity, improve efficiency and reducing cycle time by controlling the melting process. Another important factor is that the effective insulation of the melting furnace because, it suffers heavy wear and stresses due to the continuous filling and emptying of molten glass, it is important to manage the heat applied.

Glass manufacturing has been known for several hundred years, but still recently depended solely on empirical knowledge which, is model of the process is developed based upon the observed behavior of the process in response to the test signals applied to the process. It had been event that machine production which brought about the research of processes taking place in the sequence of the full glassmaking procedure, starting with batch preparation and ending with final treatment and finishing of the products. The configuration in Figure 2.1 uses raw materials that are automatically mixed and fed into the furnace where they are heated and fused at 1200° - 1300°C [20, 21, 22].

Like in other industries, the quality of products plays a important part, and together with energy consumption is the subject of primary interest of all glass manufacturers [25]. However, there has not yet been and isn't likely to be found within the nearest future, any standard criterion for assessing the quality of the glass melt being produced, which would express its quality by one objective characteristic [26]. Therefore, the quality is described by the subsequent factors:

- degree of melting
- degree of refining

The final quality of glass is clearly determined for the foremost part by the processes taking place within the glass furnace. The quality and thus also the homogeneity of glass is known to be strongly affected by the flow of glass in the furnace and by the parameters affecting the flow, such as the furnace design, the thermal barrier, and in the case of fossil fuels heating, also the shape, arrangement, and wiring of fossil fuels design the furnace tank.

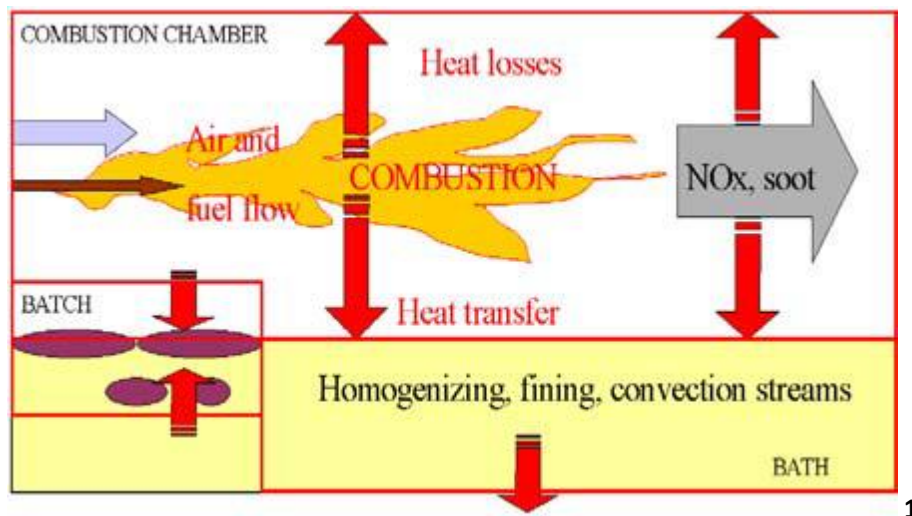


Figure 2.1 Physical phenomenon [26]

Raw Materials: The largest proportions of raw material comprise of sand, soda ash, limestone, and recycled glass are called cullet. Other additives are made in the order of portions of a percent in order to achieve, as an example, the proper glass color. The proportions of raw material are weighed and mixed very carefully in a controlled batch plant according the established process knowledge of proportional requirements found from the results of chemical and physical experiments. For this thesis, established raw material mixing is assumed to be correct.

The mixed raw materials, called a batch, are supplied to the furnace and automatically fed into the melting end as a required. The criterion for control of batch supply to the melting end is that of molten glass level in the furnace. Bubbles might also result in the ultimate product as see in Figure 2.2.

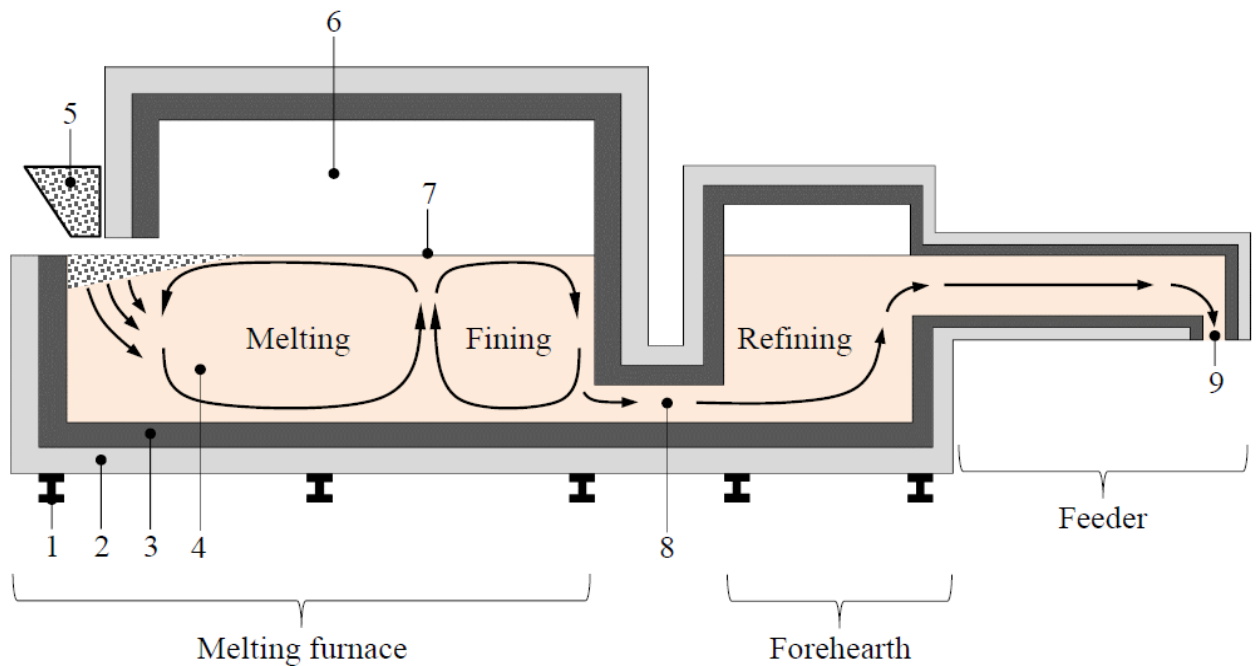


Figure 2.2 glass melting tanker [19, 20]

Schematic to illustrate the glass melting tanker.

- 1) the steel girder
- 2) thermal insulation
- 3) the refractory walls
- 4) the glass bath
- 5) the batch charging
- 6) combustion chamber
- 7) hot spots
- 8) throats
- 9) Discharging outlets.

The system illustrated in see Figure 2.2 consists of a melting furnace, a forehearth, and feeders. For the development, refractory elements, mostly of the fused cast alumina-zirconia-silica (AZS) type, are used [19, 20]. There's a layer of thermal insulation elements on the outside of the furnace to cut back the Wall heat losses. The full construction stands on supporting steel girders.

The melting furnace could be a large tank with a joint Combustion chamber above where the melting stage takes place. The tank contains a capacity of dozens of cubic meters and the melting surface is dozens of square meters in area. The batch is fed into one or more openings with in the sides of the tank, forming a blanket on the glass melt. The heat fusing the disparate batch materials is steadily transferred from the combustion chamber to the surface of the glass bath by radiation and convection. It comes from fossil fuel burners that shoot horizontal flames above the glass bath surface.

2.2.2 Batch Mixing

Batch mixing, also called “batching,” includes the creation of a mixture of raw materials designed to produce the desired end product. Batching which is mixed of raw materials may be divided into five groups supported their function within the melting process like glass formers, fluxes, property modifiers, colorants and fining agents. Although formulae for batch mixtures vary greatly among producers and are highly dependent on the planned use of the finished product, the majority of batch material utilized in a combination is usually a glass former. Glass formers are the compounds that make the structural basis of the glass. The foremost common glass formers are silica(SiO_2), boric oxide(B_2O_3), and phosphoric oxide(P_2O_5). Common names of glasses are based on the types of Glass former utilized in the batch material [15].

Flux is a compound that's added to the batch to lower the melting temperature of the glass former. Pure silica has a melting temperature of over 2100°C. By Adding of a flux to the batch mixture can lower the melting temperature by over 500°C. The foremost common fluxes are salt (sodium oxide Na_2O) mixed with sodium carbonate (Na_2CO_3), limestone ($CaCO_3$) and potassium carbonate (potash, K_2CO_3). Lead oxide (PbO), is that the compound used to make crystal glass, is additionally an efficient fluxing agent, but usage is decreasing due to environmental regulations concerning heavy metals. Adding flux to the batch will decrease the melting temperature, but weaken the chemical structure of the glass. Adding property modifiers,

such as alumina (AlO_3), will increase the robustness of the chemical structure. Batch procedures are designed to balance the results of the flux and also the property modifier in a manner that uniforms the required purpose of the finished product.

Colorants are chemical compounds added to the batch mixture to make a desired color in the finished glass. Most colorants are conversion metals including iron, manganese, cobalt, copper, chromium, and tungsten. Conversion metals have valence electrons (the electrons that combine with other elements) in more than one shell or level. Since each level of the conversion metal absorbs light of a different frequency, the visible colors are a result of electron transmission between valence levels within the ion. Further colorants, including sulfur and selenium, replace a number of the oxygen within the glass and form new compounds with different absorption characteristics than the batch compounds [16].

Fining agents are used to aid remove bubbles from the molten glass. Bubbles can be caused by chemical reactions during the melting process, breakdown of the refractory lining of the furnace or by gasses trapped between batch particles. These bubbles must be removed to improve the standard of the glass. Compounds including arsenic and antimony oxides (As_2O_5 , Sb_2O_5), potassium and sodium nitrates (KNO_3 , $NaNO_3$), salt, ($NaCl$), sulfate (SO_3), and several other fluorides (CaF_2 , NaF , $NaAlF_6$) can be added separately or together combination with the fining portion of glass production. Small bubbles within the molten glass are carried to the surface with larger bubbles formed by chemical reactions induced by the addition of the fining agents.

2.2.3 Furnace Charging

Furnace charging is the process by which the raw materials are fed into the furnace. Materials are added to the furnaces either continuously or in batches. Continuous batch feeding is accomplished with the employment of either a screw, blanket or pusher type charger. All three sorts of chargers push the batch material into the furnace at a gradual rate. A screw charger is a large helical auger that moves the batch toward the furnace as it rotates. Blanket chargers push horizontal lines of batch towards the furnace with an extended bar and pusher chargers feed small amounts of the batch into the middle of the melted by means of a locking mechanism.

Batch charging is employed on furnaces with capacities but 10 tons per day. Batch charging could be a manual procedure; employees use moves to load batch materials into a furnace. Some operations require small amounts of a batch to be added to the furnace 2-3 times per hour, while other operations only load batch once per day.

2.2.4 Melting Process

The melting process converts raw materials to molten glass. This process is often divided into 4 stages: melting, fining, homogenizing and heat conditioning. These stages don't seem to be completely sequential from the charging end of the furnace to the forming end. Instead, the stages overlap because the materials progress towards the outlet of the furnace. For a batch furnace, the position of the stages along the length of the furnace can be equated to the time from loading the batch to the removal of the glass.

2.2.4.1 Melting

Melting begins upon the introduction of the batch material to the charging end of the furnace. As heat is added to the furnace, water within the batch evaporates and chemical compounds break down and start to transition to a liquid stage. The evaporation of water decreases the quantity of the melt and increases the energy consumption of the furnace, but the presence of water cannot be eliminated. Many of the compounds in batch materials are hygroscopic and can absorb water from the atmosphere. Also, raw materials are often sprayed with water to decrease dust during mixing and transportation. Because the chemical compounds break down and become liquid, several gasses, including CO_2 , SO_2 , and SO_3 , are formed. The formation of those gasses produces a bubble that has been removed before the forming process [17].

Flow of Batch: When fed from the batch feeder, the batch is placed on to the surface of the molten glass in the furnace in batch piles which, due to currents within the molten glass, move forward down the furnace as they melt. The way during which they melt is extremely important and contains a significant touching on the way during which heat is supplied to the furnace. The foremost concentrated heating of the batch loads occurs at their surface, causing a flow of molten glass right down to the pile to the main body of the glass. The flow of newly-melted batch, down the batch piles, results in the unmelted batch being exposed and thus allows the process to

continue. The temperature inside the batch piles remains very low, heat diffusion of the pile being poor. Thus, it is energetic that the batch piles are completely melted before they reach the bridge wall Figure 1.1. The currents in the glass at the bridge wall would result in any unmelted batch being dragged down into the molten glass. This has a serious effect on the quality of glass produced causing impurities known as seed and stone to be produced.

Firing: To melt the raw material, heat must be supplied to the furnace. The way within which this is often processed varies from the furnace to furnace but during this case; it's achieved by a cross-fired regenerative process, firing either gas or oil. This is often supplemented by an electrical boost supplied by electrodes through the furnace floor. The method of regenerative firing is of specific implication in isolation of the specific objectives of the research, but briefly, cross-fired regenerative furnaces can be described as having ports on each side of the melting end in Figure 1.1 Through this ports-a. The mixture of fuel and pre-heated air is burnt, first from the ports on one side then from the opposite. Whilst firing from one side, the expend gases tolerate the alternative ports and expend through a regenerator. This regenerator then stores heat in preparation for pre-heating the air incoming when firing within the opposite direction. The time between these firing reversals will be preset and is usually between fifteen and twenty minutes.

Although the fuel to the two ports is controlled on an individual port basis, the combustion air is supplied only as a complete flow to it that particular side. The right fuel/air ratio is obtained by the individual port sizes.

2.2.4.2 Homogenizing

The homogenizing phase of melting begins with initially melting and ends when the material in the furnace reaches the point at which the melt is free of batch material and of relatively uniform consistency. The degree of homogeneity required is predicated on the required properties of the formed product. The homogenizing phase includes the complete melting and fining phases because the compounds within the melt are continually reacting to create the ultimately product. Factors that affect the time required for a melt to homogenize include particle size of the batch materials, a mixture of batch materials, temperature, and mixing patterns from either mechanical or convective currents.

2.2.4.3 Heat Conditioning

The heat conditioning stage is that the time period during which the melt is transported to the temperature required for the planned forming process. Heat conditioning creates a uniform temperature in the portion of glass at the forming end of the furnace. The time required for heat conditioning is dependent upon the amount of the glass in the forming end, the desired forming temperature and the flow rate of glass to the forming process.

2.2.4.4 Fining

The removal of bubbles within the melt occurs in the fining stage. Bubble velocity is relies upon size, larger bubbles will quickly rise to the highest of the melt. Small bubbles move so slowly that the time required to achieve the surface can cause delays in production. The occurrence of fining agents within the batch material aids within the removal of small bubbles by creating larger bubbles which will carry the small bubbles to the surface. Making an upward flow within the melt can help increase the speed of bubble increase. Mechanical stirring, or compressed gas forced through outlets located within the bottom of a tank, can be used to produce the necessary current. The creation of hotter and cooler sections of a furnace by localized heating can induce convective currents that promote fining and the geometric design of the bottom of the furnace can also produce the desired upward flow.

2.2.5 Throat

The throat in Figure 1.1 is a way of restricting flow into the working end to only allow homogeneous molten glass at approximately the right temperature. This is often simply achieved by its position, which is characteristic within the design of the furnace and its effectiveness depends on many factors, a number of which have already been mentioned. These factors include the correct melting of batch piles and also the nature of the present flow pattern in the melt.

2.2.6 Working end

Ideally, the significance of the throat is that the working end should comprise only pure molten glass at a temperature suitable for pass to the forehearth (approx. 1200°C), Figure 1.1. Thus, the

correct properties required for glass manufacture are present. The working end also refines the metal to a reasonably close specification. (For this reason, the working end is additionally called the refiner.) This refining process is further extended in the individual forehearth.

2.2.7 Forehearth, Feeders and Forming

Upon entering the forehearth the metal then undergoes the conditioning process during which uniform viscosity is obtained. This needs cooling the metal to about 1090°C by means of a closely controlled process involving extra burners and air channels. At the end of the forehearth, the spout or feeder is reached. In the spout, a rotating cylinder ensures a good temperature supply, whilst a plunger moves up and down inside the cylinder to force the glass through an orifice. This produces a quantity of glass referred to as gob, which is sheared off by automatic cutters before being delivered to the forming machine. The gob, by use of various orifice sizes, plunger strokes, etc. Orifice sizes is a set size and weight at the correct temperature to manufacture a specific variety of glass. Forming is an automatic process involving complex, if somewhat traditional techniques, details of which are unimportant in the context of this work.

2.3 PID Controller

A proportional-integral-derivative controller (PID) could be a feedback controller that's widely employed in many control applications. The main function of the PID controller is to reduce the error, A PID calculates the error between the measured process variable and desired point then gives a corrective action to manage the process according to the set point and to keep the error as low as possible. The proportional term gives a response supported the present error; the integral value regulates the action supported the sum of recent errors and derivative value gives the response supported the rate at which error changes is given to the PID controller as shown in Figure 2.3. This PID controller can be series combination or parallel combination of the proportional term, derivative term and integral term. [39]. The equation of the PID is given as

$$u(t) = K_P e(t) + K_I \int_0^t e(t) dt + K_D \frac{de(t)}{dt} \quad (2.1)$$

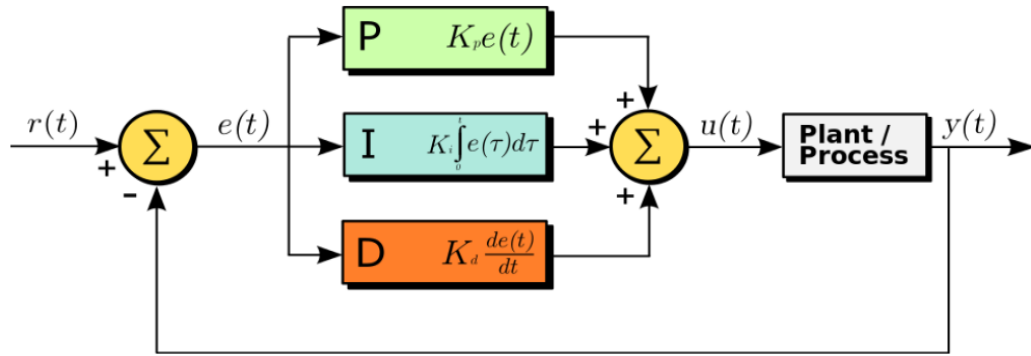


Figure 2.3 General block diagram of PID [40]

Proportional Control: The proportional term depends on the current error value by making a change to the output that is proportional to the current error value. The response term could be attuned by multiplying the error by a constant K_p , which is proportional gain and is given by.

$$P_{out} = K_p e(t) \quad (2.2)$$

Where P_{out} = output of the proportional term K_p = proportional gain and e = Error. A high proportional gain will lead to a large change in the output for a given change in the error. A Larger (P) gain values provides a faster response but it's make a system unstable and a small (P) gain will lead to a less responsive or sensitive controller due to which the control action may be too small while responding to system disturbances. If the error is large which means proportional term compensation is additionally large. Within the PID controller, it's mainly the proportional term that creates a serious contribution to the output change [40].

Integral Control: accounts for past values of the error. The integral term is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output. Also when the integral time (T_i) is large the response of the controller is slower and when it's small the response is faster. The Integration of error gives the accumulated offset that is multiplied by the integration gain and added to controller output. The magnitude of the general contribution of the integral term is set by the integral gain.

$$I_{out} = K_I \int_0^t e(t) dt \quad (2.3)$$

Here, I_{out} = Integral output, K_I = Integral gain, e = error, and t is the instantaneous time.. With large values of integral gain (I), the residual steady-state error is eliminated faster but the outcome is large overshoot. Any negative value of error integrated during the transient response must be integrated by the positive error before reaching a steady-state error. The integral term responds to the accumulated errors from the past so it should cause this present value to overshoot the set point, therefore a mix of PI controller gives a stronger output.

Derivative Control: The rate of change of process error is calculated by determining the derivative of the error with respect to time and the contribution of the derivative term is given by derivative gain K_d .

$$D_{OUT} = K_d \frac{de(t)}{dt} \quad (2.4)$$

where, D_{out} is derivative output, K_d is derivative gain, e is error and t is instantaneous time The main function of the derivative term shows the rate of change of controller output and its effect is seen close to the set point.

The function of the derivative term is to reduce the overshoot caused by the integral term and to improve the combined performance of the controller. A large values of Derivative gain (K_d) overshoot created by integral term could be reduced but could also lead to signal noise amplification with the differentiation of the error. The differential control is mainly utilized to suppress the noise caused by the derivative.

- **The characteristics of P, I, and D controllers**

A proportional controller (K_p) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady-state error. An integral control (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control (K_d) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. Effects of each of controllers K_p , K_i , and K_d on a closed-loop system are summarized in the table-2.1 [59].

Table 2. 1 Effects of increasing a parameter independent P, I and D tuning

Parameter	Rise Time	Overshoot	Settling Time	Steady-State Error
Increasing K_p	Decrease	Increase	Small Increase	Decrease
Increasing K_i	Small Decrease	Increasing	Increase	large Decrease
Increasing K_d	Small Decrease	Decrease	Decrease	Minor Change

2.4 Adaptive control

the Adaptive control use to signify a change of behavior in order to handle new situations and uncertain circumstances. Similarly, we can think of adaptive controllers as controllers that can modify their behavior to adapt parameters of the controller in order to deal with uncertainties.

The adaptive controller takes certain references or set points to follow and some input and output measurements. Some or all of the plant parameters may not be exactly known, and as such, the adaptation mechanism tries to identify the individual parameters or lumped versions. It before passes this information to the controller, which in turn adapts its behavior based on the updated system information.

In a controlled process, if the process parameters are either little known or very unexpectedly during operation, the adaptive control technique can be useful so as to obtain a precise, accurate and safe working control system. Landau, [37] defined adaptive control as a set of techniques for automatic adjustment in real-time of controllers in order to accomplish or maintain a desired level of performance of a control system when the process parameters are unknown or change with time. The basic idea in adaptive control is to estimate the uncertainties in the plant (or equivalently, in the corresponding controller) on-line based on the measured signals [27].

In general adaptive control system has two loops. The first one is the normal feedback which uses to compare the set point with the actual output of the plant and the second one is the loop

which uses for adjustment of the controller parameters. There are different types of adaptive control system such as model reference adaptive control, gain scheduling, self-tuning regulators, dual control etc. in this thesis it is selected model reference adaptive control (MRAC) for designing the adaptive control of glass melting furnace. Figure 2.4 shows the general schematic diagram for an adaptive control system.

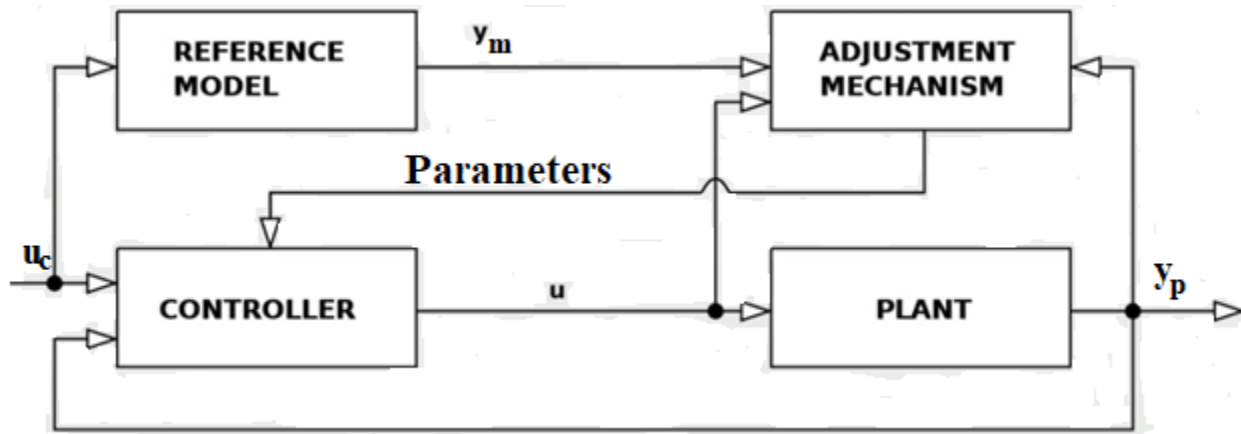


Figure 2.4 Block diagram of an Adaptive control system [33].

2.4.1 Model Reference Adaptive Control (MRAC)

Model reference adaptive control is an objectively general approach to design and the main organizations used in adaptive systems. In MRAC the performance specifications of a system are given in terms of reference model. This model tells us how the system should respond to a command signal. The controller can be thought of as consisting two loops. The inner loop is an ordinary feedback loop composed of the process and the controller. The outer loop adjusts the controller parameters in such a way that the error i.e. the goal is to minimize the error between plant output and reference model output [31]. The controller parameters can be updated by using the adaptation mechanism. The block diagram for MRAC is shown in Figure 2.5.

2.4.1.1 Theoretical Modeling of MRAC Using MIT Rule

The MIT rule is the first approach to Model Reference Adaptive Control. The name is resulting from the fact that it was developed at the Instrumentation Laboratory at Massachusetts Institute of Technology (MIT), U.S.A. The adaptation law aids in obtaining a set of parameters that

reduce the error between the plant and the model outputs. Hence the parameters of the controller are adjusted until the error becomes zero [38].

To present the MIT rule, both inner and outer loops of the system are considered in which the controller has two adjustable parameters. The desired closed-loop response is specified by a model output (y_m). The tracking error (e) is the difference between the output of the system (y_p) and the output of the reference model (y_m). The tracking error (e) is given by equation

$$e = y_p - y_m \quad (2.5)$$

To reduce the error, one possibility is to adjust parameters in such a way that the loss function $J(\theta)$ is minimized

$$J(\theta) = \frac{1}{2}e^2(\theta) \quad (2.6)$$

where θ is the plant adaptation parameter.

To minimize $J(\theta)$, MIT rule adjust the parameters are changed in the direction of the negative gradient of J is,

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} = \gamma e \frac{\partial e}{\partial \theta} \quad (2.7)$$

The partial derivative $e \frac{\partial e}{\partial \theta}$ is called the sensitivity derivative of the system which tells how the error is influenced by the adjustable parameter. γ , is the adaptation gain [37,30].

MIT Algorithm: To see how the MIT rule can be used to form an adaptive controller, a system with an adaptive feedback gain is considered. The structure consists of four main parts: the plant, the controller, the reference model and the adjustment mechanism as shown in Figure 2.5. In this system, G_m and G_p is used as the model and plant transfer functions. The input to output relationship is determined to basing on the transfer functions within the adaptive control strategy.

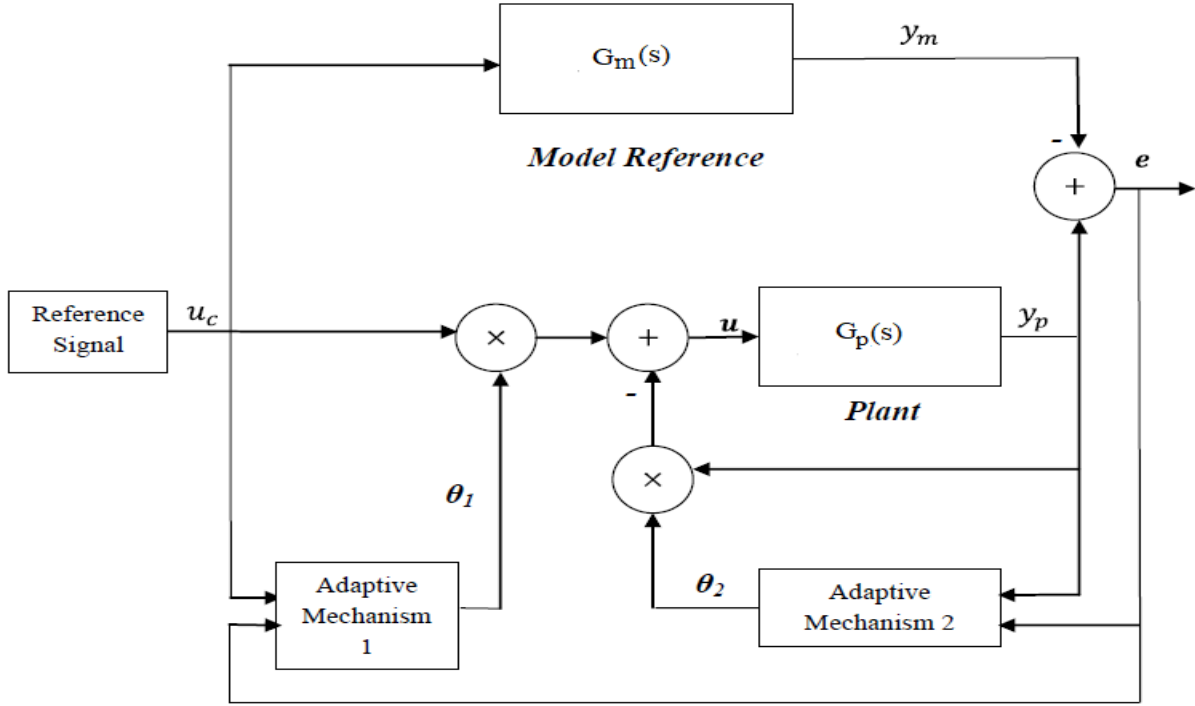


Figure 2.5 Block diagram of an Adaptive Control System [38]

$$\frac{Y_p(s)}{u(s)} = G_p(s) \quad (2.8)$$

$$\frac{Y_m(s)}{u_c(s)} = G_m(s) \quad (2.9)$$

However, using the same cost function in equation (2.6) We have

$$J(s) = \frac{1}{2} e^2(\theta) \rightarrow \frac{d\theta}{dt} = -\gamma e \frac{\partial e}{\partial \theta} \quad (2.10)$$

The error in equation (2.1) is then restated in terms of the transfer functions multiplied by their inputs.

$$e = G_p u - G_m u_c \quad (2.11)$$

$$e = G_p \theta u_c - G u_c \quad (2.12)$$

To determine the update rule, the sensitivity derivative was calculated and restated in terms of the model output:

$$\frac{\partial e}{\partial \theta} = G_p u_c \quad (2.13)$$

$$G_p u_c = Y_m \quad (2.14)$$

Therefore

$$\frac{\partial e}{\partial \theta} = Y_m \quad (2.15)$$

The MIT rule is applied to give an expression for updating.

$$\frac{d\theta}{dt} = -\gamma Y_m e \quad (2.16)$$

It is assumed that the controller has an adaptive feedback θ gain as illustrated in Figure 2.6.

2.4.1.2 Lyapunov Stability Method

The Lyapunov stability method is an important class of adaptive control. This method attempts to find the Lyapunov function and an adaptation mechanism in such a way that the error between plant and model goes to zero. The structure consists of four main parts: the plant, the controller, the reference model and the adjustment mechanism as shown in Figure 2.5.

Lyapunov theory for time invariant systems fundamental contribution to the stability theory for nonlinear system. Lyapunov investigated the nonlinear differential equation.

$$\frac{dx}{dt} = f(x) \quad f(x) = 0$$

Since $f(x) = 0$ the equation has the solution $x(t) = 0$

To guarantee existence of a unique solution, it is necessary to make some assumptions about (x) . A sufficient assumption is that $f(x)$ is locally Lipschitz, that is

$$\|f(x) - f(y)\| \leq L \|x - y\| \quad L > 0$$

in the neighborhood of the origin.

2.5 Related Works

The control of the glass melting furnace has been widely studied in the literature using various control techniques in recent years. But most of them are worked on a glass melting furnace to control a single variable like temperature without consideration of the linearization of the variable. In fact, there are also some researches that consider the linearization of the variable, in which most of them use a conventional PID controller. The following points are the review of related works done previously.

Real J. Fradette, in [10] has developed “Understanding PID Temperature Control as Applied to Vacuum Furnace Performance”. PID controller was used to control the temperature of the vacuum furnace at a desired temperature for the process, such as 1500°F. The PID parameters are tuned using Ziegler Nichols tuning algorithm. The problem with this controller is that the parameters of the controller are constant. So the result shows poor performance with high overshoot, large settling time and large rise time for the constant set point temperature.

Fekolin & Stupak [9] patented an arrangement for refining and homogenizing optical glasses in crucibles using artificial Lorentz forces. In this case, the model comprises arrangement consists in three pairs of electrodes and two electromagnets. A glycerin-based model liquid physical which is based on the similarity theory to investigate the electromagnetic stirring in electrically heated feeders. They studied the dependence of the liquid’s maximum velocity in the stirring zone on the magnetic flux density magnitude at different electric currents applied to the electrodes. However, the problem with this process is as the similarity criteria of the temperature dependent material properties are not considered, results from such a model remain unsure.

Naif B. Almutairi and Mohamed Zribi, in [11] have developed “Sliding mode controllers for a tempered glass furnace”. They investigated the design of sliding mode controllers (SMCs) introduced a nonlinear transformation that maps the dynamic model of the tempered glass furnace into the generalized controller canonical form to facilitate the design of controller. The main objective of the proposed controllers is to regulate the glass plate temperature. The problem here is , they considers only two stores energy such as the upper-wall temperature and the lower Wall temperature in the furnace to a common desired temperature. They didn’t consider the

energy balance in the combustion gasses to the refractory wall and the glass which can be inefficient to the melting.

Peyman Nazarian, in reference [12] has developed “Feedback Linearization based control of a horizontal radioactive furnace”. For the control of this horizontal radioactive furnace, which generally used for producing the tempered glass. In this work, feedback linearization technique has been applied by considering the working temperature range, as well as working area. The arrival of the control system is, its ability to attain the set temperature at the set time and also to maintain it. The limitation of this work is it introduces steady state error.

Moon and Lee in [14] studied a modeling technique for a glass furnace in which the linear part of the furnace dynamics was modeled by a First-Order- Plus-Dead-Time (FOPDT) system and the nonlinear part of the furnace was modeled by fuzzy logic system. The problem with this model doesn't consider the process between the gas input and the throat temperature output which is the Predicted glass temperature such as combustion gas temperature, crown temperature and refractory floor temperature can also be not used as a feedback for the controller.

A similar kind of modeling was also proposed by Leendert Huisman [15], Schobben [16] and Wattamwar [17]. They studied to obtain a fast and reduced simulation model for estimation and control of glass melt temperatures in glass melting tanks and glass melt feeders. In these works, a fast reduced simulation model of a glass furnace was derived from a detailed first-principles model (CFD model) by using the POD technique in combination with system identification. However, the problem with this controller they are complicated and they consume a lot of CPU time to simulate the dynamics of the system with sufficient accuracy. Due to this, such models cannot be used in applications that require short computation time (for example model-based control).

Form the above review it is clear that different works of literature are reviewed about glass melting furnace process, glass properties and temperature controllers that have been used in this work. As far as I now adaptive controller for temperature control of the glass melting-process is not modeled. Therefore, in this work, a fault-tolerant adaptive, PID temperature controller is modeled and simulated.

CHAPTER THREE

Mathematical Model of Glass Melting Furnace

This chapter introduces the materials and methods used in the design and analysis of the temperature control for the glass melting furnace. Designing the combustion chamber, this is fundamental to the developed methods for the models. It is possible to fundamentally develop further methods for the glass furnace models. The mathematical model derived from radiative heat transfer was applied here to analyze the temperature distribution within the combustion chamber, which is divided into four-parts.

The developed combustion chamber based on radiative heat transfer is divided into four-parts and, the enclosure's walls surface parts improved the heat flux and temperature distribution within the combustion chamber. The nonlinearity relationship within energy balances (conservation law) shows an analytical complication due to the dependency of radiative heat flow rates on the temperature. The model is nonlinear which has to be linearize using Taylor series linearization technique in order to implement a controller and improved the linear relationship in energy balances. The physical properties of the selected combustion chamber model are studied.

Linearizing energy balance equation in steady-state is used to improve the prediction and accuracy of temperature distribution within four-parts. An assessment of selected glass furnace models, which is designed by the four part method, provides a greater insight into model understanding and performance quantitative.

3.1 Modeling Of Glass Melting Process

The first step in the analysis and design of the control system is the mathematical modeling of the different components. Commonly used in designing control systems is transfer function technique. After proper assumptions and approximations are complete to linearize the mathematical equations describing the components, then obtained the transfer functions. Thus, using these transfer functions, the melting process is modeled for temperature control. The main components of the

glass melting process of the heating section. Before designing the temperature control system, the appropriate model for each component should be obtained.

3.2 Technical Methodology

Glass quality and workability are highly dependent upon temperature. The thermal and mechanical properties of glass vary greatly with temperature; therefore, it is desired to maintain a near-constant glass temperature particularly during homogenizing and working periods. Modern control systems monitor the temperature of combustion gasses near the top of the furnace by means of a shielded thermocouple placed in the crown. Temperature set points are maintained by changes in the flow rate of fuel to the burner. The combustion gas temperature is correlated to the rate of heat transfer to the glass. In furnaces, the thermocouple is separated from the glass by the flame. Variations within the sensed temperature are delayed only by the time constant of the thermocouple and the propagation of the flame from the burner to the location of the thermocouple. The sensed temperature delay is very small which compared to the time constant of the entire system because it does not include the thermal capacitance of the glass or the refractory walls.

3.2.1 Energy Balance Equation

To monitor the behavior of the glass temperature in relation to the measured crown temperatures, an energy balance was performed using thermodynamic and energy conservation laws. The model used for this thesis was a lumped-parameter, simplified model of the furnace and its contents.

The first law gives a quantitative relation of the energy balance equation by the variation with time, t , of the heat generated within the sample, Q , due to the absorption of light of incident power P_i is given by:

$$\frac{\partial Q}{\partial t} = P_i - q \quad (3.1)$$

Where, q is the power losses by radiation, convection, and conduction. For this thesis, radiation is the only mechanism taken into account for energy balance formulation due to its predomination. Thus, the parameter q should be some function of the temperatures, T_1 and T_2 , of

both the regions involved. It is denoted as the heat flux. In general, the dependence of the heat flux on the temperature is non-linear.

The continuous energy interchange between separated bodies by means of electromagnetic waves, heat transfers between two adjacent elements i and j at temperatures T_i and T_j and (flow cell i with flow cell j or with wall element j) presenting a common area A_{ij} is very simply computed by :

$$q_{ij} = A_{ij}H_{ij}(T_i - T_j)$$

The net rate of heat flow, q_{rad} , radiated by a body surrounded by a medium at a temperature T_1 is given by the Stefan-Boltzmann Law,

$$q_{rad} = \varepsilon\delta A(T_2^4 - T_1^4) \quad (3.2)$$

where the A is the surface area of the radiating object and ε is the total emissivity of its surface having absolute temperature T_2 . To compute the rise of temperature, ΔT , of the back sample's surface, the heat transfer must be expressed as a function of temperature which is increasing or decreasing. It is given by the relationship,

$$Q = \rho cV\Delta T \quad (3.3)$$

Where ρ the density, c is the specific heat and $V = AL$ is the sample's volume. Differentiation of (3.3) with respect to time and substitution into (3.1) leads to:

$$\frac{\partial \Delta T}{\partial t} + \frac{q}{\rho cV} - \frac{P_i}{\rho cV} \quad (3.4)$$

Where q_{rad} is specified as radiation terms given by (3.2). As described by nonlinear relationships, the rates of radiative heat flow are dependent on the temperature. This nonlinearity makes the system complex for the analytical solution of the energy conservation law given by (3.4). An indication at (3.2) shows that if the temperature difference $\Delta T = T_2 - T_1$ is small, then one could expand it as a Taylor series around T_1 obtaining a linear relationship:

$$q = 4\varepsilon\sigma A\bar{T}_1^3(T_2 - T_1) = hA\Delta T \quad (3.5)$$

The $H = 4\epsilon\sigma\bar{T}_1^3$ can be considered as a radiation heat transfer coefficient. This linearized energy balance equation is accurate above 1200K [7]

3.2.2 Model of Combustion Chamber

The combustion chamber is to determine the heat release of the combustion reaction. We have first to determine the flow in the enclosure, the compositions of the atmosphere and the associated combustion reaction. The heat transfers we have to compute by radiation and convection to the load and to the surrounding (losses) [7]. It is possible to develop a state- space model of an end-fired furnace in which the furnace was divided into four parts. Distinct states are identified for the temperatures of the refractory in the crown, the walls above the glass melt, the walls adjacent to the melt zones, and the floor of the furnace. In all, state variables are included in the model. The inputs are the net thermal power provided by the flame and the ambient temperature. In this thesis, the flow is first the definition of mass transfers between cells, and we assume it one-directional in the direction of the flames. Then, the volumetric flows depend on the input flows of fuel and air and on the combustion reaction.

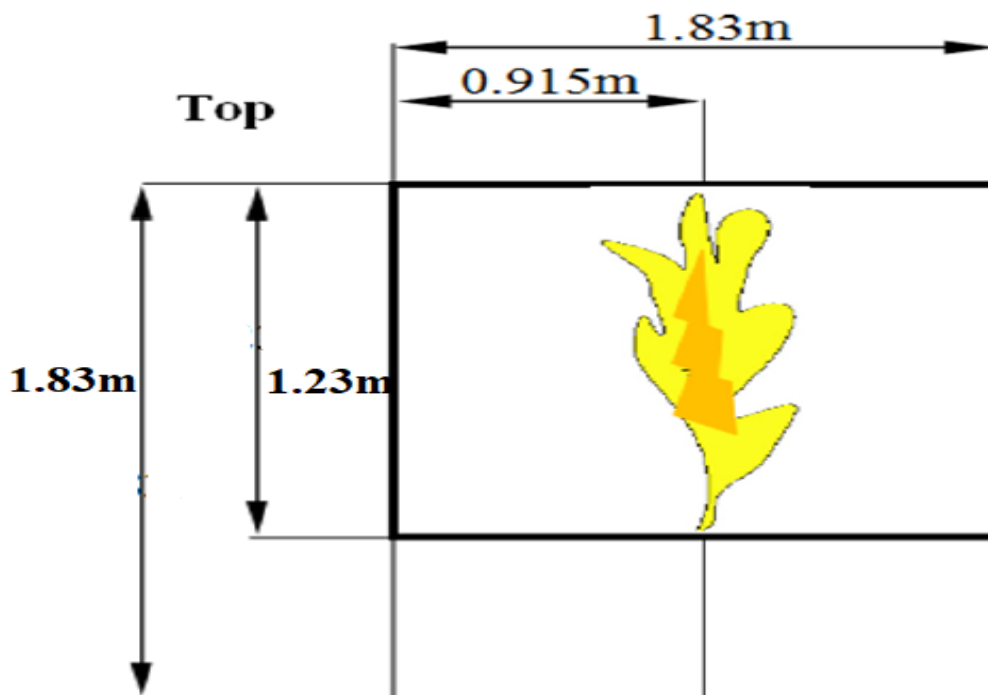


Figure 3.1 Furnace Combustion [18]

Consequently, the heat transfer equation is simpler and gives fewer temperature states within the furnace. However, different volumes have different temperatures, which allows for variations in temperature along the length and height of the furnace. Refractory volumes consist of only the inner high-temperature layer. A furnace is constructed using two layers, inner and outer of refractory. The inner layer is an extreme temperature refractory that is designed to resist the corrosion of the glass. The outer layer consists of a lighter and insulating refractory.

The final volume is the top half of the glass volume and the bottom of the glass in the chamber. The temperature within each volume of glass and gas is assumed uniform and feedback to the controller to sustain the glass temperature. The linearized energy balance equation (3.15) is applied and modified with related variables for each gas and surface zones to identify state-space variables corresponding to temperatures.

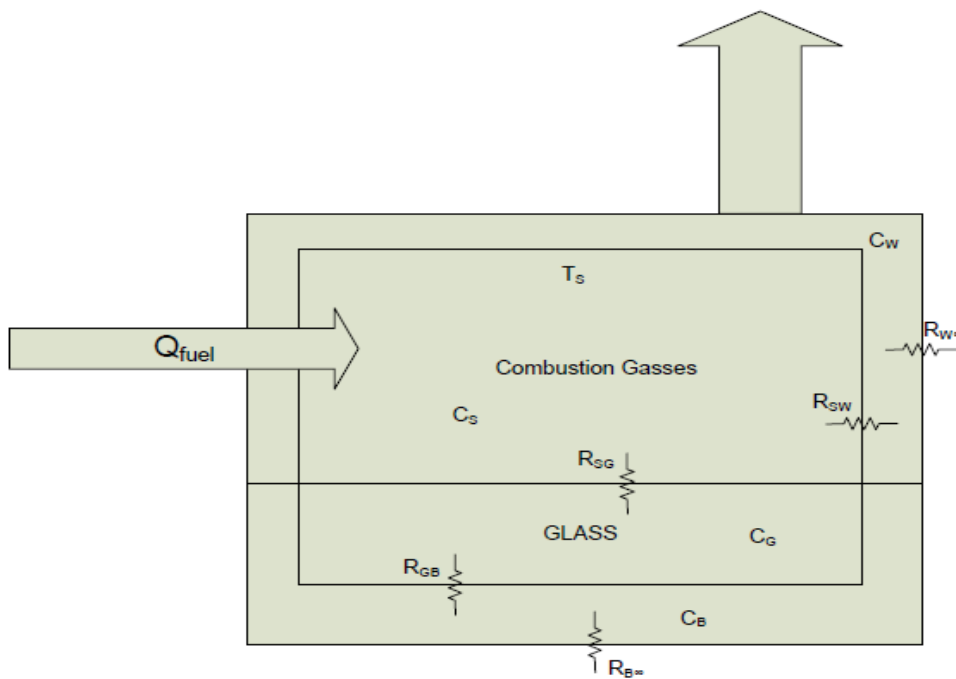


Figure 3. 2Heat Balance Diagram

The energy balance was divided into four parts depending on the component of the system that stores the energy. These parts related subscripts are as follows: the combustion gases (S), the

glass (G), the refractory structure at the bottom of the furnace that is in contact with the glass (B) and the refractory structure above the surface of the glass (W).

For the combustion gas energy, balance the energy sources are: \dot{Q}_{fuel} The energy drops are: \dot{Q}_S , \dot{Q}_G and \dot{Q}_W , law of Conservation of Energy states that:

$$\dot{Q}_{fuel} = \dot{Q}_S + \dot{Q}_G + \dot{Q}_W \quad (3.6)$$

Due to the high-temperature environment and characteristics of the system, radiation is the dominant mode of heat transfer from the combustion gasses to the refractory wall and the glass. The convection coefficient has been shown to be more than two orders of magnitude smaller than the radiation coefficient.

From radiates heat transfer has the form:

$$\dot{Q} = \varepsilon\sigma A(T_2^4 - T_1^4) \quad (3.7)$$

The mean temperature of the combustion gasses and the glass temperature were used to linearize the heat transfer function and results in the following form:

$$\dot{Q} = 4\varepsilon\sigma\bar{T}_1^3 (T_2 - T_1) \quad (3.8)$$

The linearized form is

$$\dot{Q} = HA(T_2 - T_1) \quad (3.9)$$

Where H is a generalized coefficient of heat transfer and A is the parameter area. The coefficients of heat transfer for the combustion gasses to the glass and to the wall are respectively:

$$H_{SG} = 4\varepsilon\sigma\bar{T}_{SG} \frac{W}{m^2K}$$

$$H_{SW} = 4\varepsilon\sigma\bar{T}_{SW} \frac{W}{m^2K}$$

Where:

ε is the emissivity of combustion gasses

σ is Stephan-Boltzmann constant ($5.67 \times 10^{-8} \frac{W}{K^4m^2}$)

$$\bar{T}_{SG} = \frac{T_S + T_G}{2} (K)$$

$$\bar{T}_{SW} = \frac{T_S + T_W}{2} (K)$$

T_S = Temperature of combustion gasses (K) this is the temperature measured by the thermocouple and for the purposes of this model , assumed to be approximately the same as the temperature of the stack gasses

T_W is Temperature of furnace wall (K)

T_G is Temperature of glass (k)

Rearranging and increasing the energy balance equation for combustion gasses gives:

$$\dot{m}c_{ps} \frac{dT_S}{dt} = \dot{Q}_{fuel} - \frac{A_W}{R_{SW}} (T_S - T_W) - \frac{A_G}{A_{SG}} (T_S - T_G) \quad (3.10)$$

where :

$c_s = \dot{m}c_{ps}$ the capacitance of the combustion gasses ps m&c

$\frac{dT_S}{dt}$ is the time rate of change of the temperature of the combustion gasses

A_W is the area of the refractory surface above the glass level (m^2)

A_G is the surface area of the glass (m^2)

$$R_{SG} = \frac{1}{H_{SG}} \frac{m^2}{W} K$$

$$R_{SG} = \frac{1}{H_{SG}} \frac{m^2}{W} K$$

After development and rearrangement the heat transfer calculation for the combustion gases in, T_G is,

$$c_G \frac{dT_G}{dt} = \frac{A_G}{R_{SG}} (T_S - T_G) - \frac{A_B}{R_{GB}} (T_G - T_B) \quad (3.11)$$

Where:

$c_G = m\dot{c}_{PG}$ is the capacitance of the glass

$\frac{dT_G}{dt}$ is the time rate of change of the temperature of the glass

A_G is the area of the refractory surface in contact with the glass (m^2)

A_B is the temperature of the refractory in contact with the glass (K)

$R_{SG} = \frac{1}{H_{SG}}$ with H_{SG} the heat transfer coefficient between the combustion gasses and the glass.

$R_{GB} = \frac{1}{H_{GB}} = \frac{m^2}{W} K$ with H_{GB} the heat transfer coefficient between the glass and the refractory

The energy balance equation for the refractory in contact with the glass is then:

$$C_B \frac{dT_B}{dx} = \frac{A_B}{A_{GB}} (T_G - T_B) - \frac{A_B}{A_{B\infty}} (T_B - T_\infty) \quad (3.12)$$

Where:

$C_B = m\dot{c}_{PB}$ the capacitance of the refractory

$\frac{dT_B}{dt}$ Is the time rate of change of the temperature of the refractory in contact

With the glass

$R_{B\infty} = \frac{1}{H_{B\infty}} \frac{m^2}{W} K$ with $H_{B\infty}$ the heat transfer coefficient between the refractory and the environment

T_∞ is the temperature of the environment (K) And the energy balance equation for the refractory above the glass is. The energy balance equation for the refractory above the glass is:

$$c_w \frac{dT_W}{dt} = \frac{A_W}{R_{GW}} (T_S - T_W) - \frac{A_W}{R_{W\infty}} (T_W - T_\infty) \quad (3.13)$$

Where:

$$c_w = \dot{m} c_{PW} = m \& cp \text{ W the capacitance of the refractory}$$

$\frac{dT_W}{dt}$ is the time rate of change of the temperature of the refractory above the

Surface of the glass

$$R_{W\infty} = \frac{1}{H_{W\infty}} \frac{m^2}{W} \text{K with } H_{W\infty} \text{ the heat transfer coefficient between the}$$

refractory and the environment.

Combining like terms from Equations (3.10), (3.11), (3.12) and (3.13) as follows and dividing by capacitance, we obtain the set of equations as:

$$\begin{aligned} \frac{dT_S}{dt} &= \frac{\dot{Q}_{fuel}}{c_S} - \left(\frac{A_W}{R_{SW}c_S} - \frac{A_G}{R_{SG}c_S} \right) T_S + \left(\frac{A_W}{R_{SW}c_S} \right) T_W + \left(\frac{A_G}{R_{SW}c_S} \right) T_G \\ \frac{dT_G}{dt} &= \left(\frac{A_G}{R_{SG}c_G} \right) T_S - \left(\frac{A_B}{R_{SG}c_G} + \frac{A_G}{R_{GB}c_G} \right) T_G + \left(\frac{A_B}{R_{B\infty}c_S} \right) T_B \\ \frac{dT_B}{dt} &= \left(\frac{A_B}{R_{GB}c_B} \right) T_B - \left(\frac{A_B}{R_{GB}c_B} + \frac{A_B}{R_{B\infty}c_B} \right) T_B + \left(\frac{A_B}{R_{B\infty}c_B} \right) T_\infty \\ \frac{dT_W}{dx} &= \left(\frac{A_W}{R_{GW}c_W} \right) T_S - \left(\frac{A_W}{R_{GW}c_W} + \frac{A_W}{R_{W\infty}c_W} \right) T_W + \left(\frac{A_W}{R_{W\infty}c_W} \right) T_\infty \end{aligned} \quad (3.14)$$

3.3 State-Space Model Representation

The state-space matrix of glass furnace process that was working in the above can be written in following general form;

$$\begin{aligned}\dot{X}(t) &= A(t)X(t) + B(t)U(t) \\ Y(t) &= c(t)X(t) + D(t)U(t)\end{aligned}\quad (3.15)$$

where, $X(t)$ is the state vector, $X(t) \in R^4$; y is the output vector, $y(t) \in R^1$; $U(t)$ is the input (control) vector, $U(t) \in R^1$; $A(\cdot)$ is the state (system) matrix, $\dim[A] = 4 \times 4$; B is the input matrix; $\dim[B] = 4 \times 2$; C is the output matrix, $\dim[C] = 1 \times 4$; D is the feed-forward matrix; $\dim[D] = 1 \times 2$. The A of glass furnace is the individual temperatures in respective volumes. The B consists of the heat input (Q_{fuel}) and the ambient air temperature (T_{amp}). The C consists of the glass temperature (T_G) for control. The D is zero since there is no direct connection between inputs and T_G . The state variables are the temperatures of the combustion gasses, glass, bottom refractory and wall refractory. The inputs are flame energy and environment temperature. The desired output is the temperature of the glass, and disturbance is considered to be a zero matrix. Equations 3.10 and 3.13 are arranged in state-space form as follows:

$$\frac{d}{dt} \begin{bmatrix} T_S \\ T_G \\ T_B \\ T_W \end{bmatrix} = \begin{bmatrix} -\left(\frac{A_W}{R_{SW}c_S} + \frac{A_G}{R_{SG}c_S}\right) & \frac{A_G}{R_{SG}c_S} & 0 & \frac{A_W}{R_{SW}c_S} \\ \frac{A_G}{R_{SG}c_G} & -\left(\frac{A_G}{R_{SG}c_G} + \frac{A_B}{R_{SG}c_G}\right) & \frac{A_G}{R_{GB}c_G} & 0 \\ 0 & \frac{A_B}{R_{GB}c_B} & -\left(\frac{A_B}{R_{GB}c_G} + \frac{A_B}{R_{GB}c_G}\right) & 0 \\ \frac{A_W}{R_{GW}c_W} & 0 & 0 & -\left(\frac{A_W}{R_{GW}c_B} + \frac{A_W}{R_{W\infty}c_W}\right) \end{bmatrix} \begin{bmatrix} T_S \\ T_G \\ T_B \\ T_W \end{bmatrix} + \begin{bmatrix} \frac{1}{c_S} & 0 \\ 0 & 0 \\ 0 & \frac{A_B}{R_{B\infty}c_B} \\ 0 & \frac{A_B}{A_{W\infty}c_W} \end{bmatrix} \begin{bmatrix} \dot{Q}_{fuel} \\ T_\infty \end{bmatrix}$$

$$[Y] = [0 \ 1 \ 0 \ 0] \begin{bmatrix} T_S \\ T_G \\ T_B \\ T_W \end{bmatrix} + [0 \ 0] \begin{bmatrix} \dot{Q}_{fuel} \\ T_{amp} \end{bmatrix}\quad (3.16)$$

Numeric values for the variables in the state and input matrices are needed in order to determine the controllability of the system. Values were determined as follows:

$c_s = \dot{m}_s c_{p_s}$ is the capacitance of the combustion gasses

The mass of the combustion gas is determined using the ideal gas law,

$$\dot{m}_s = \frac{P_s V_s}{R_s T_s}$$

$C_G = \dot{m}_g c_G$ the capacitance of the glass

The mass of the glass is: $R_s = \frac{R_W}{Mw} = \frac{8314 \frac{J}{Kmol.k}}{30.28 \frac{kg}{Kmol}}$ which is Constant for combustion gas base on the average molecular weight of stoichiometric products of methane combustion with air

$P_s = 101325 \frac{N}{m^2}$; is the pressure within the furnace assumed to be atmospheric for this model

$V_s = 0.3423m^3$ is the volume of the furnace containing combustion gas

$T_s = 1300K$ mean combustion gas temperature during operation and Combustion gas specific heat can be estimated as $1.025 \frac{KJ}{kg.k}$

Capacitance for the combustion gas is then:

$$C_s = mc = 0.1 \frac{kJ}{K}$$

The Values for glass properties have been take [8] are:

$$\rho_G = 2.43 \frac{g}{cm^3} = 2430 \frac{kg}{m^3}$$

$$C_g = 1.24 \frac{J}{g.k} = 1.24 \frac{kJ}{Kg.k}$$

The mass of the glass is then given by:

$$\dot{m}_g = V_G \rho_G = 0.567 * 2429 \frac{kg}{m^3} = 1370 kg$$

And the capacitance of the glass is:

$$C_G = \dot{m}_g C_g = 1700 \frac{kg}{k}$$

$C_B = \dot{m}_b c_B$ is the capacitance of the refractory the mass of the refractor sections is:

$$\dot{m}_b = V_B \rho_B$$

The density of the refractory is:

$$\rho_B = \rho_W = 3.81 \frac{g}{cm^3} = 3180 \frac{kg}{m^3}$$

The specific heat value for the refractory is:

$$C_B = C_W = 1.18 \frac{KJ}{kg.k}$$

$C_W = \dot{m}_w c_w$ is the capacitance of the refractory and is given by:

$$\dot{m}_w = V_W \rho_W$$

The mass of the refractory sections are obtained as:

$$\dot{m}_B = V_B \rho_B = 1.73 m^3 * 3180 \frac{kg}{m^3} = 5500 kg$$

$$\dot{m}_W = V_W \rho_W = 1.45 m^3 * 3180 \frac{kg}{m^3} = 4670 kg$$

Then the capacitance values are:

$$C_B = \dot{m}_B C_B = 6500 \frac{KJ}{K}$$

$$C_W = \dot{m}_W C_W = 5440 \frac{KJ}{K}$$

Since the numerical values produced in this section are intended to be initial conditions, the resistance values for both radiation terms (R_{SW} and R_{SG}) were calculated using an initial mean temperature of 1300K. The resulting value is:

$$R_{SW} = R_{SG} = \frac{1}{4\sigma\epsilon\bar{T}_1^3} = \frac{1}{4(5.67 * 10^{-8})(0.3)(1300)^3} = 0.0068 \frac{m^2k}{W} = 6.8 \frac{m^2k}{kW}$$

The resistance between the refractory and the environment was calculating from surface conductance values available in literature [10]. The resistance values are:

$$R_{B\infty} = R_{W\infty} = \frac{1}{0.0073} = 138 \frac{m^2k}{kW}$$

The resistance term between the molten glass and the refractory was assumed to be roughly equivalent to the contact resistance between molten glass and mold during a forming process [11]. The value is then:

$$R_{GW} = \frac{1}{500} = 0.002 \frac{m^2k}{KW}$$

Specification of the glass melting furnace for the given model

Table3.1 Variables used in modeling glass melting furnace

Variable	Description	Value	unit
A_G	area of the refractory surface in contact with the glass	1.49	m^2
A_B	area of the refractory surface in contact with the glass	2.61	
A_W	the area of the refractory surface above the glass level	3.31	
C_S	the capacitance of the combustion gasses	0.1	$\frac{kJ}{K}$
C_G	the capacitance of the glass	1700	
C_B	the capacitance of the refractory	6500	
C_W	the capacitance of the refractory	5450	
R_{SW}	the heat transfer coefficient between the combustion gasses and the refractory	6.7	$\frac{m^2k}{kW}$
R_{SG}	the heat transfer coefficient between the combustion gasses and the glass	6.7	
$R_{B\infty} = R_{W\infty}$	the heat transfer coefficient between the refractory and the environment	139	
R_{GB}	heat transfer coefficient between the Glass and the refractory	2	

The parameters of the state-space model with fuel as input and temperature as output are expressed as follow:

$$\frac{d}{dt} \begin{bmatrix} T_S \\ T_G \\ T_B \\ T_W \end{bmatrix} = \begin{bmatrix} -6.14 & 2.23 & 0 & 3.91 \\ 0.000131 & -0.00111 & 0.0009834 & 0 \\ 0 & 0.000257 & -0.0002614 & 0 \\ 0.00001716 & 0 & 0 & -0.0000755 \end{bmatrix} \begin{bmatrix} T_S \\ T_G \\ T_B \\ T_W \end{bmatrix} + \begin{bmatrix} 10 \\ 0 \\ 0 \\ 0 \end{bmatrix} [Q_{fuel}]$$

$$y = [0 \ 1 \ 0 \ 0] \begin{bmatrix} T_S \\ T_G \\ T_B \\ T_W \end{bmatrix} + [0 \ 0] [Q_{fuel}] \quad (3.17)$$

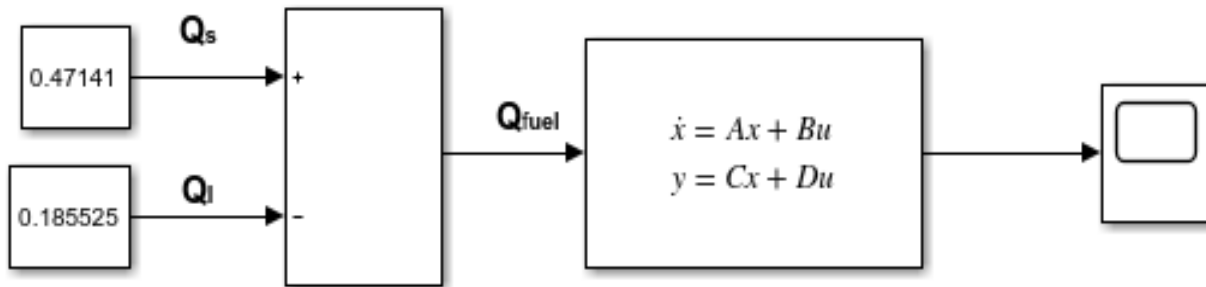


Figure 3. 3Simulink state-space model

Table3.2 variables of the Available Energy to Furnace

Variable	Descriptions	Value	Unit
Q_f	the energy available to the process	-	J/s
Q_s	the energy available from the combustion	0.47141	J/s
Q_l	the stack energy loss	0.185525	J/s
c_s	the approximated specific heat of the combustion	1.025	kJ/kgK
A/F	is the air-fuel ratio. The stoichiometric value	17.2	-
LHV	the lower heating value of methane	49770	kJ/kg

The input fuel control section to control the \dot{m}_{fuel} according to the temperature feedback error(u).The energy available to the process is a function of the mass flow rate of fuel, flame, air and ambient temperatures, the heating value of the fuel and the specific heat of the combustion products. The relationship between ideal energy from the fuel and energy available to the process was derived is shown below. The most important requirement to be met in respect of feeding is to keep the glass level to a constant value. If the furnace air is lower or higher than the atmospheric air, shoot out from the opening or flames cold air may stream into the furnace. The air inside the furnace is kept constant, somewhat above the atmospheric air. The temperature of the melted glass affects the chemical reactions going within the glass. Temperature set points are maintained by changes in the flow rate of fuel to the burner.

$$Q_{fuel} = \dot{Q}_s - \dot{Q}_l \quad (3.18)$$

$$\dot{Q}_l = c_s[(\dot{m}_f * A) + \dot{m}_f] \quad (3.19)$$

$$\dot{Q}_s = \dot{m}_f * LHV \quad (3.20)$$

$$Q_{fuel} = \dot{m}_f[LHV - (1 + A)c_s]$$

$$Q_{fuel} = \dot{m}_f \left[47.141 \frac{J}{kg} - (1 + 17.1) * 1.025 \frac{kJ}{kgK} \right] \quad (3.21)$$

$$\dot{m}_f = u * m_{maxfuel(constant)} = u * 0.01 \frac{kg}{s} \quad (3.22)$$

$$Q_{fuel} = u * \left(0.47141 \frac{J}{s} - 0.185525 \frac{J}{s} \right) = u * 0.285885 \frac{J}{s} \quad (3.23)$$

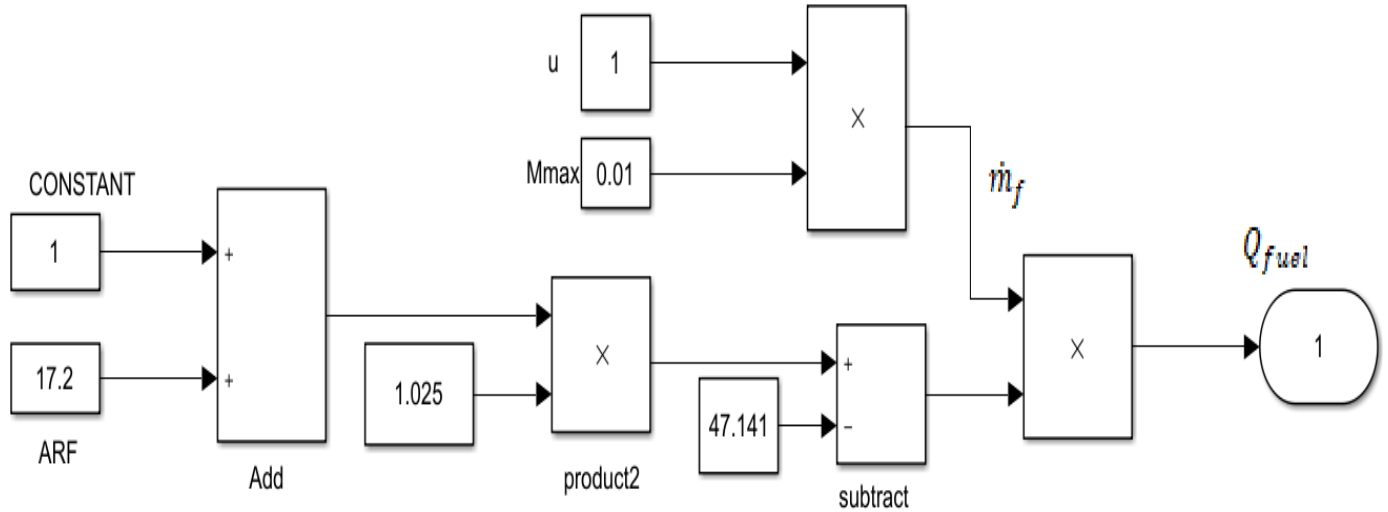


Figure 3.4 Simulink Diagram of the Subsystem in the Open-Loop Model of Furnace

Simple algebraic operation with Laplace transform gives transfer functions as follows:

$$\begin{aligned} X &= A\dot{X} + BU \\ y &= CX + DY \end{aligned} \quad (3.24)$$

The transfer matrix $G(s)$ is a matrix that related $Y(s)$ and $u(s)$ as follows:

$$Y(s) = G(s)U(s)$$

Taking Laplace transforms of the state space equation, we obtain

$$SX(s) - x(0) = AX(s) + BU(s) \quad (3.25)$$

$$Y(s) = CX(s) + Du(s) \quad (3.26)$$

In deriving the transfer matrix, we assume that $x(0)=0$ then from equation (3.25), we get

$$X(s) = (sI - A)^{-1}BU(s) \quad (3.27)$$

Substituting equation (3.27) into equation (3.26) we obtain

$$G(s) = [C(sI - A)^{-1}B + D]U$$

Thus the transfer matrix $G(s)$ is given by

$$G(s) = C(sI - A)^{-1}B$$

The transfer matrix $G(s)$ for the given system becomes

$$G(s) = C(SI - A)^{-1}B$$

$$G(s) = [0 \ 1 \ 0 \ 0] \begin{bmatrix} s + 6.14 & -2.23 & 0 & -3.91 \\ -0.000131 & s + 0.00111 & -0.0009834 & 0 \\ 0 & -0.000257 & s + 0.00026 & 0 \\ -0.0000716 & 0 & 0 & s + 0.0000755 \end{bmatrix}^{-1} \begin{bmatrix} 10 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Hence

$$\frac{y(s)}{u(s)} = G(s) = \frac{0.1340s^2}{s^4 + 6.1414s^3 + 0.0083s^2} \quad (3.28)$$

3.4 Modeling of Temperature Sensor

Temperature can be measured with a variety of instruments that respond to temperature with an electrical signal, including thermocouples, thermistors, RTDs (resistance thermometry devices), etc. In this section, we address both the static (calibration) and dynamic (time response) characteristics of temperature sensors [58, 59].

Calibration of the sensor is determining the relationship between the actual quantity of interest (the temperature at some location in the glass) and the output given by the sensor (which can be a voltage, a current in a circuit, a digital representation, etc. depending on the instrument). When we speak of a sensor, we usually refer to both the sensing element (such as the bimetallic junction of a thermocouple) and signal conditioning electronics. It is this latter component that produces a linear relationship between temperature and sensor output, even though the behavior of the sensing element itself may be nonlinear [58, 59].

Thus we relate the physical temperature T_o and its sensor reading T_s given by [58]:

$$T_s = K_s T_o + b_s \quad (2.29)$$

In a handheld digital thermometer, the electronics are adjusted so that gain K_s is unity and bias b_s is zero: 26°C produces a reading of 26°C. In a control loop, however, we are more likely to have produces an electric current that ranges over 4 to 20 mA, where these limits correspond to

the expected range of temperature variation. Current loops are a good way to transmit signals over the sorts of distances that separate operating processes from their control rooms.

The sensor range is adjusted by varying and suppose that we wish to follow over the range 1200°C to 1300°C. Then

$$4mA = K_s 1200^\circ\text{C} + b_s \quad (2.30)$$

$$20mA = k_s 1300^\circ\text{C} + b_s \quad (2.31)$$

Thus, $K_s = 0.16mA K^{-1}$ and $b_s = -188mA$

We express the sensor calibration in deviation variables by subtracting the reference state from (1). Suppose we wish to use 1250°C as a reference operating condition. At the reference, the sensor output will be 12 mA [58].

Sensor response is first-order. Hence, we may write the sensor transfer function as

$$T_s(s) = \frac{K_s}{\tau_s s + 1} T_o(s) \quad (2.32)$$

Where

- ✓ $T_s(s)$ is sensor reading
- ✓ $T_o(s)$ is physical temperature the system
- ✓ K_s is the sensor gain that was determined by calibration in (2.30) , (2.31)and most of the time it is unity.
- ✓ τ_s is a time constant that depends on the mass of the sensor element and the rate of heat transfer to the sensor.

When the sensor is immersed in to the medium, the heat transferred to the sensor in the time interval dt .

$$d\theta = \alpha A(\theta - \theta_T)dt \quad (2.33)$$

The heat stored in the sensor:

$$dQ = mcdQ_T \quad (2.34)$$

Thus,

$$\alpha A(\theta - \theta_T)dt = mcd\theta_T \quad (2.35)$$

$$\frac{mc}{\alpha A} \frac{d\theta_T}{dt} + \theta_T = \theta \quad (2.36)$$

Hence, $\tau_s = \frac{mc}{\alpha A}$

Where,

- ✓ α is coefficient of heat transfer
- ✓ A is the surface area of the sensor
- ✓ c is the heat capacity
- ✓ m is mass of sensor

The values of τ_s is taking assumptions that equal to 10s.

$$\theta_T(S) = \frac{1}{\tau_s s + 1} \theta(s) \quad = \quad T_S(s) = \frac{K_s}{\tau_s s + 1} T_o(s) \quad (3.37)$$

CHAPTER FOUR

Design of Control System

There are different types of controllers used for temperature control of glass melting furnace where PID and MRAC Controllers will be discussed in the following section.

4.1 Design and analysis of PID

PID controller can be understood as a controller that takes the present, the past, and the future of the error into consideration. Tuning a control loop is the adjustment of its control parameters (proportional band/gain, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response. Stability (bounded oscillation) is a basic requirement, but beyond that, different systems have different behavior, different applications have different requirements, and requirements may conflict one with another. The transfer function $G_c(s)$ of the PID controller is [39-41]

$$G_c = K_p + \frac{K_i}{s} + K_d s \quad (4.1)$$

In this thesis, we first present the design of a PID controller for the glass melting furnace using MATLAB/Simulink automatic tuning.

4.1.1 Simulink Model of PID Controller for The Glass Melting Furnace

In this thesis the PID controller gains are tuned automatically for different ranges of robustness. The Simulink model system of Glass melting furnace for the temperature control using PID controller is given below. The sensor used is thermocouple and mathematically modeled as a first order system.

4.1.2 Temperature Control

The closed loop plant for temperature with PID controller is developed in MATLAB Simulink as shown in figure 3.6. The PID controller gains are tuned automatically and the values of the gains

for a robustness of 0.6 are $K_p = 0.1053$, $K_i = 0.0001759$, $k_d = 4.7114$ and filter coefficient (N)=0.0050 ,N is the tuning factor ,which is need to make the controller transfer function proper.

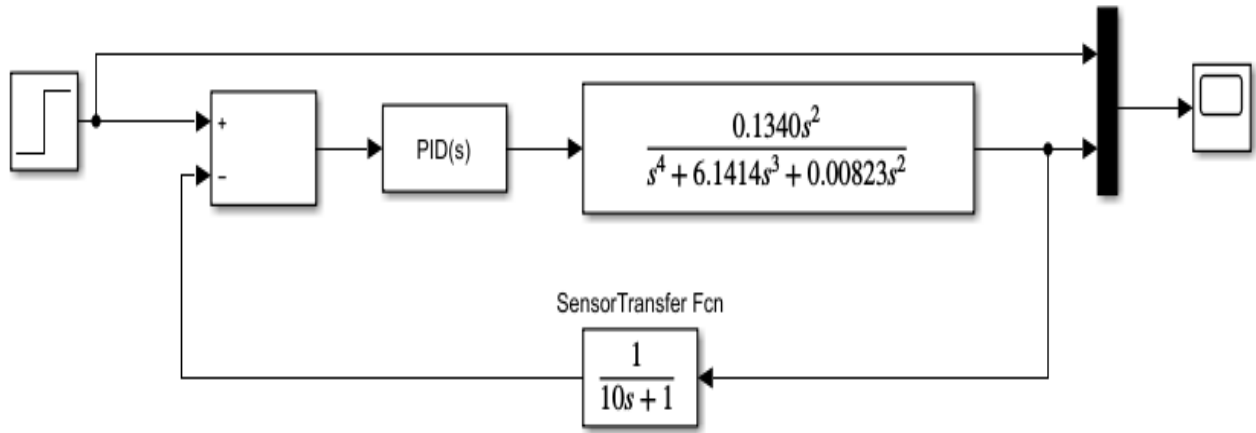


Figure 4.

Figure4. 1Simulink model of PID controller

4.2 Design of Model Reference Adaptive Control

Model Reference Adaptive Control strategy is used to design the adaptive controller that works on the principle of adjusting the controller parameters so that the output of the actual plant tracks the output of a reference model having the same reference input. The general structure of the Model Reference Adaptive Control (MRAC) system illustrates in Figure 2.5. The basic MRAC system consists of 4 main components:

Plant: to be controlled

Reference Model: It is used to generate desired closed-loop output response of the adaptive control system to the reference input.

Controller: that is time-varying and whose coefficients are adjusted by adaptive mechanism and it is usually defined by a set of modifiable parameters. The system has two parameters θ_1 and θ_2 is used to describe the control law $u = \theta_1 u_c - \theta_2 \left(\frac{1}{10s+1} \right) y$. The speed of convergence of θ to the optimal value is dependent on adaptation gain.

Adjustment Mechanism: This component is used to alter the parameters of the controller so that the actual plant could track the reference model. Adaptation in MRAC takes the form of adjustment of some or all of the controller coefficients so as to force the response of the resulting closed-loop control system to that of the reference model. Mathematical approaches like MIT rule, Lyapunov theory, and theory of augmented error can be used to develop the adjusting mechanism.

In designing the MRAC controller, we would like the output of the closed-loop system y , to follow the output of the reference model y_m . Therefore, we aim to minimize the error $e(t) = y(t) - y_m(t)$ by designing a controller that has one or more adjustable parameters such that a certain cost function is minimized.

4.2.1 Determination of the Model Reference Transfer function

Considering the assumption of the linearity of our process (motorized damper valve), the process will be a second-order system. The standard form of the second-order system is given by the following expression:

$$G_m = \frac{w_n^2}{s^2 + 2\delta w_n s + w_n^2} \quad (4.2)$$

The required specifications for the temperature control system are assumed to be a maximum Overshoot of 2 % and a settling time (t_s) of less than 3 seconds. The main aim was to determine the damping ratio and natural frequency for the system such that the transient response to step input satisfies the stated conditions ($t_s \leq 3\text{sec}$ and $\%OS \leq 2\%$). The percentage overshoot is supposed to be less than 2%, hence;

$$\%OS = e^{\frac{\delta\pi}{\sqrt{1-\delta^2}}} \times 100\% = 2\% \quad (4.3)$$

From this we obtain $\delta = 0.9447$

The undamped natural frequency was determined using the condition $t_s < 3\text{sec}$ such that;

$$t_s = \frac{4}{\delta w_n} \quad (4.4)$$

Thus

$$\frac{4}{\delta w_n} \leq 3 \quad w_n \geq \frac{4}{3\delta} \quad (4.5)$$

From which we obtain: $w_n \geq 1.7904 \text{ rads}^{-1}$

Inserting the values in the transfer function we get:

In this thesis, the underdamped second-order system is chosen as reference model G_m with damping ratio and natural frequency whose transfer function is given by

$$G_m = \frac{360}{s^2 + 36s + 360} \quad (4.6)$$

The formulated model reference transfer function was then incorporated into the Simulink model for simulation purposes. The Simulink model is shown in Figure 3.4

4.2.2 MIT Rule-Based MRAC

The system has a normal feedback loop composed of the process and the controller. The other feedback loop changes the controller parameters. The parameters are changed based on the feedback error, which is the difference between the output of the system and the output of the reference model. The parameter adaptation mechanism in MRAC can be obtained in two ways using the gradient method and stability theory. In MRAC the desired behavior of the system is specified by a model.

The MIT rule is the first approach to MRAC, its name is derived from the fact that it was developed at the instrumentation laboratory, at MIT. To present the MIT rule, we will consider a closed-loop system in which the controller has one adjustable parameter θ . The desired closed-loop system is specified by the model whose output is y_m . Let the error be the difference between the actual output y and the model y_m . The objective is to adjust the parameter so that the loss function

$$e = y - y_m \quad (4.7)$$

One possibility is to adjust parameters in such a way the loss function

$$J(\theta) = \frac{1}{2} e^2$$

Is minimized. To make J small, it is reasonable to adjust the parameters in the direction of the negative gradient of J, is:

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} = \gamma e \frac{\partial e}{\partial \theta} \quad (4.8)$$

The partial derivative $e \frac{\partial e}{\partial \theta}$ is called the sensitivity derivative of the system which tells how the error is influenced by the adjustable parameter. γ , is the adaptation gain. This implies how the error is affected by the adjustable parameter.

Mathematical Model and Analysis: The glass melting furnace plant is described by the transfer functions and a controller by the form as indicated in (3.28). In MRAC system the controller parameters have updated a function of the error between the actual plant and reference model as well as the error between the actual plant and the reference input. So since the controller parameters are updated in terms of reference model y_m , plant output y , error $y - y_m$ and $u_c - y$. A closed-loop system with a controller that has the following parameters:

- ✓ u_c = Reference input signal
- ✓ $u(t)$ = Control signal
- ✓ $y(t)$ = Plant output
- ✓ $y_m(t)$ = Reference model output
- ✓ $e(t)$ = Difference between plant and reference model output
- ✓ $e(t) = y(t) - y_m(t)$

The control objective is to adjust the controller parameters, θ_1 and θ_2 , so that $e(t)$ is minimized. To do this, a cost function, $J(\theta)$ is chosen and minimized.

The selected controller and reference model in this thesis, controller is a combination of feedback and feedforward type as follows:

The controller, u becomes.

$$u = \theta_1 u_c - \theta_2 \left(\frac{1}{10s+1} \right) y \quad (4.9)$$

Replacing them into 3.48

- Reference model:

$$G_m(S) = \frac{360}{s^2 + 36s + 360} \quad (4.10)$$

- Notice that from Eqn. (3.28),

$$y = \frac{0.1340s^2}{s^4 + 6.1414s^3 + 0.00823s^2} u \quad (4.11)$$

- Then, after substituting (3.28) into (4.12), $u = \theta_1 u_c - \theta_2 \left(\frac{1}{10s+1} \right) y$

$$y = \frac{(0.1340s^2)\theta_1 u_c}{s^4 + 6.1414s^3 + 0.00823s^2 + (0.001340s^2)\left(\frac{1}{10s+1}\right)\theta_2} \quad (4.12)$$

And from (3.13), we have

$$y_m = \frac{360}{s^2 + 36s + 360} u_c \quad (4.13)$$

Therefore the error,

$$e = y - y_m$$

$$e = \frac{(0.1340)\theta_1 u_c}{s^4 + 6.1414s^3 + 0.00823s^2 + (0.1340s^2)\left(\frac{1}{10s+1}\right)\theta_2} - \frac{360}{s^2 + 36s + 360} u_c$$

So we have, MIT rule indicated that, the parameter updated

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} =$$

$$\frac{d\theta_1}{dt} = -\gamma e \frac{(0.1340s^2)u_c}{s^4 + 6.1414s^3 + 0.00823s^2 + (0.1340s^2)\left(\frac{1}{10s+1}\right)\theta_2}$$

And

$$\frac{d\theta_2}{dt} = -\gamma e \frac{(0.1340s^2)y}{s^4 + 6.1414s^3 + 0.00823s^2 + (0.001340s^2)(\frac{1}{10s+1})\theta_2}$$

In this case, we need to do some approximation: i.e. perfect model following, $y = y_m$. Therefore, we then have,

$$\begin{aligned} \frac{d\theta_1}{dt} &= -\gamma e \frac{360}{s^2 + 36s + 360} u_c = -\gamma e y_m \\ \theta_1 &= -\frac{\gamma}{s} e \frac{360}{s^2 + 36s + 360} u_c = -\frac{\gamma}{s} e y_m \\ \frac{d\theta_2}{dt} &= -\gamma e \frac{360}{s^2 + 36s + 360} y = -\gamma e G_m y \\ \theta_2 &= -\frac{\gamma}{s} e \frac{360}{s^2 + 36s + 360} y = -\frac{\gamma}{s} e G_m y \end{aligned}$$

The MRAC gradient approach is then simulated using Matlab SIMULINK block with the reference input of a step wave signal with amplitude and frequency. Both the output of the system responses (y and y_m) are coupled and placed onto scope for simultaneous viewing. The scope is used to simultaneously observe the output response of y and the desired output response of y_m .

4.2.3 Lyapunov stability method

The Lyapunov stability method is an important class of adaptive control. This method attempts to find the Lyapunov function and an adaptation mechanism in such a way that the error between plant and model goes to zero. Also, this method guarantees the stability of the control parameters of the system. In this thesis, we considered the design using the Lyapunov stability method. When applying the designing an MRAC using the Lyapunov rule, we have chosen the following: the reference model, the controller structure and the tuning gains for the adjustment mechanism. In designing an MRAC using Lyapunov Method, the following steps should be followed:

- i) Derive a differential equation for error, $e = y - y_m$ (i.e. \dot{e} , \ddot{e} , etc.) that contains the adjustable parameter, θ . From

The reference model with a differential equation shown below

$$y_m = \frac{360}{s^2 + 36s + 360} u_c \quad (3.14)$$

$$s^2 y_m + 36y_m s + 360y_m = 360u_c \quad (3.14)$$

The differential equation becomes

$$\ddot{y}_m + 36\dot{y}_m s + 360y_m = 360u_c$$

$$\ddot{y}_m = -36\dot{y}_m - 360y_m + 360u_c \quad (3.15)$$

The process to be controlled is described as follow

$$y = \frac{0.1340}{s^2 + 6.1414s + 0.00823} u \quad (3.16)$$

$$u = \theta_1 u_c - \theta_2 \alpha y$$

$$y = \frac{0.1340}{s^2 + 6.1414s + 0.00823} (\theta_1 u_c - \theta_2 \alpha y)$$

$$s^2 y + 6.1414s y + 0.00823y = 0.1340\theta_1 u_c - 0.134\alpha\theta_2 y \quad (4.17)$$

The differential equation becomes

$$\ddot{y} + 6.1414s\dot{y} + 0.00823y = 0.1340\theta_1 u_c - 0.134\alpha\theta_2 y$$

$$\ddot{y} = -6.1414s\dot{y} - 0.00823y + 0.1340\theta_1 u_c - 0.134\alpha\theta_2 y \quad (4.18)$$

Substituting Eqns (4.15) and (4.18) into $\ddot{e} = \ddot{y} - \ddot{y}_m$ thus

$$\begin{aligned} \ddot{y} - \ddot{y}_m &= -6.1414\dot{y} - 0.00823y + 0.1340\theta_1 u_c - 0.134\alpha\theta_2 y - \\ &(-36\dot{y}_m - 360y_m + 360u_c) \end{aligned} \quad (4.19)$$

$$\ddot{e} + 36\dot{e} + 360e - (359.992 + 0.134\alpha\theta_2)y + (360 - 0.134\theta_1)u_c = 0 \quad (4.20)$$

ii) Find a suitable Lyapunov function, $V(e, \theta)$ usually in a quadratic form (to ensure positive definiteness). The Lyapunov function

$$V(e, \theta_1, \theta_2) = \frac{1}{2}e^2 + \frac{1}{\gamma}[(-359.992 - 0.134\alpha\theta_2)^2 + (360 - 0.134\theta_1)^2] \quad (4.21)$$

This Lyapunov function is zero when e is zero and the controller parameters are equal to the correct values. The total derivative of V yields;

$$\begin{aligned} \dot{V} &= e \frac{de}{dt} + \frac{1}{\gamma}(-359.992 - 0.134\alpha\theta_2) \frac{d\theta_2}{dt} + \frac{1}{\gamma}(360 - 0.134\theta_1) \frac{d\theta_1}{dt} \quad (4.22) \\ &= \dot{e}e + \frac{1}{\gamma}(2)(-0.134)(-359.992 - 0.134\alpha\theta_2) \frac{d\theta_2}{dt} \\ &\quad + \frac{1}{\gamma}(2)(-0.134)(360 - 0.134\theta_1) \frac{d\theta_1}{dt} \\ &= -\frac{1}{36}(\dot{e}e + 360e^2) + (359.992 + 0.134\alpha\theta_2) \left(\frac{ye}{36} - \frac{1}{\gamma}(2)(0.134) \frac{d\theta_2}{dt} \right) \\ &\quad + (360 - 0.134\theta_1) \left(-\frac{u_c e}{36} - \frac{1}{\gamma}(2)(0.134) \frac{d\theta_1}{dt} \right) \quad (4.23) \end{aligned}$$

is negative, the above mentioned quadratic function is a Lyapunov function. If the parameter adjustment law is chosen to be

$$\begin{aligned} \frac{d\theta_1}{dt} &= -\frac{\gamma u_c e}{(2)(359.992)(0.134)} = -\gamma' u_c e \\ \frac{d\theta_2}{dt} &= \frac{\gamma y e}{(2)(359.992)(0.134)} = -\gamma' y e \end{aligned}$$

The derivative

$$\dot{V} = -\frac{1}{36}(\dot{e}e + 360e^2) \quad \gamma$$

is thus negative semi-definite. This implies that $v(t) \leq 0$ and hence e , θ_1 and θ_2 must be bounded. As a result, the output of the system $y = e + y_m$ is also bounded.

The Lyapunov stability based method avoids the stability problems present in the gradient approaches. The major difference between the gradient rule and the Lyapunov method is that the sensitivity of the error to a specified parameter $\frac{\partial e}{\partial \theta}$ has been replaced by the actual value of the parameter, θ . The adaptation law shown in the above discussion is commonly used for the first-

order or second-order system but it is proved that it can be applied for a much wider range of systems. A key result of this is that a different adaptation law need not be calculated when changing to a different plant or model unless the performance of the adaptation law is proven to be insufficient.

4.2.4 Simulink Model MIT Rule-Based MRAC for The Glass Melting Furnace

The system of glass melting furnace is designed using Simulink model given as Figure 3.7:

The approximation transfer function is given in equation (3.48)

$$\frac{y(s)}{u(s)} = G(s) = \frac{0.1340s^2}{s^4 + 6.1414s^3 + 0.00823s^2} \quad (3.58)$$

The MRAC developed in MATLAB Simulink for controlling glass melting furnace is given in Figure 3.4.

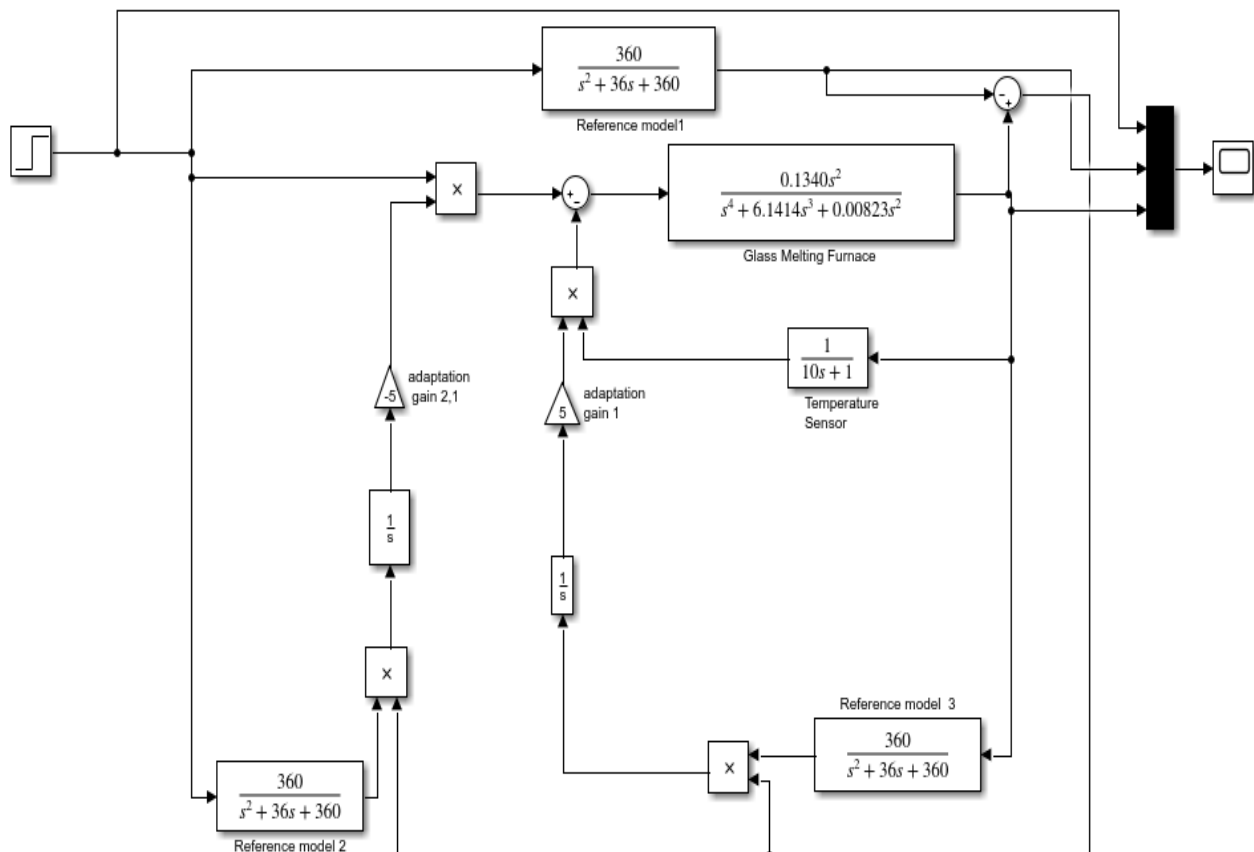


Figure4. 2 Simulink models for MRAC controller using MIT rule

4.2.5 Simulink Model of MRAC Using Lyapunov For The Glass Melting Furnace

The system of glass melting furnace is designed using Simulink model given as follows:

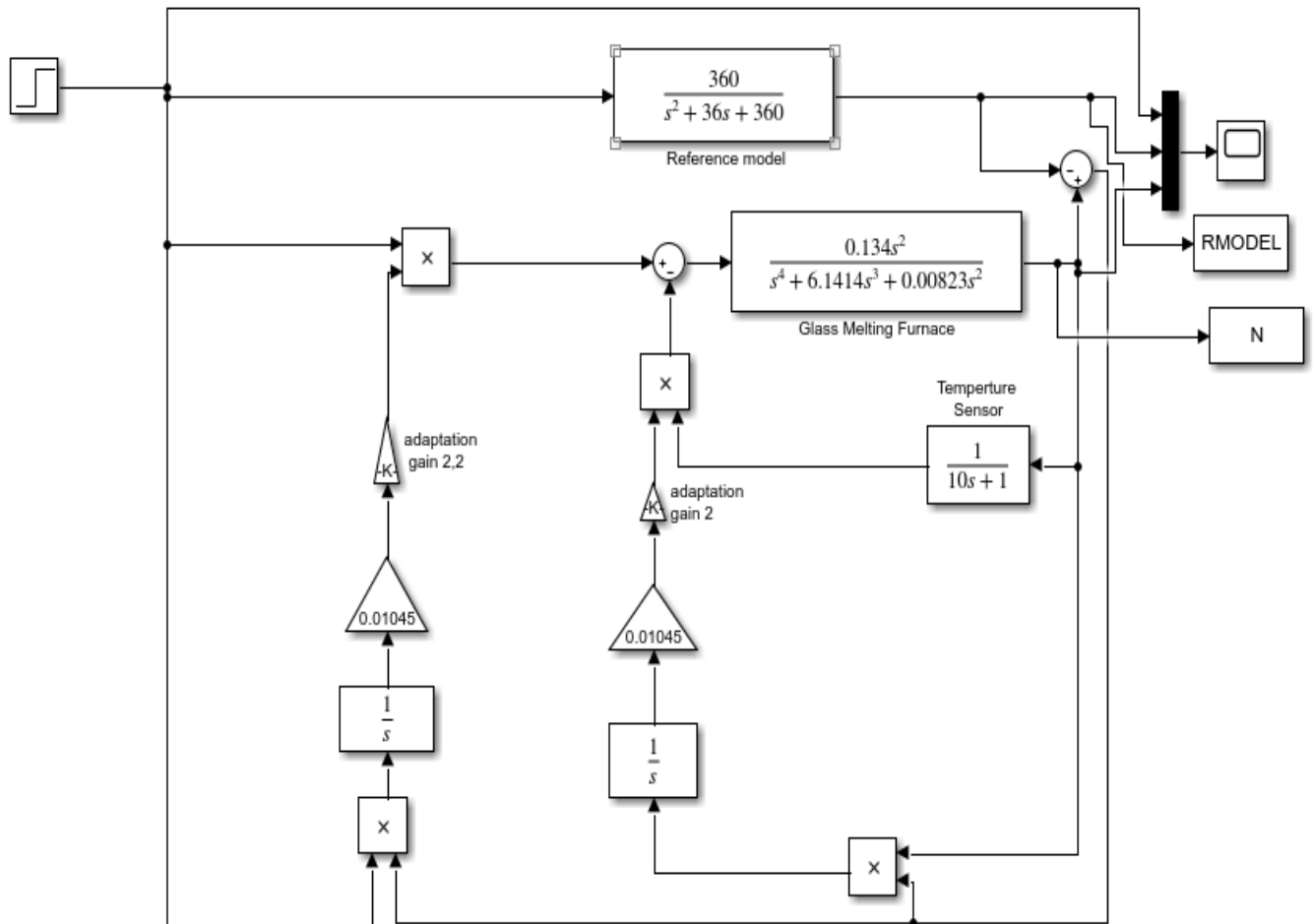


Figure4. 3Simulink models for MRAC controller using Lyapunov

CHAPTER FIVE

Simulation Results and Discussions

The temperature control for glass melting furnace was linearized, designed and analyzed in chapter three and the three methods were discussed in detail. The three methods are PID, Lyapunov and MIT rule. In this chapter, the results obtained from MATLAB simulations will be discussed. The results obtained from the closed-loop system by using PID and adaptive controllers will be compared. The simulation is analyzed by step response, disturbance rejection and parameter variation (robustness) of the closed-loop system. The MRAC is designed using the Gradient method/MIT rule has been shown that it does not guarantee stability to the resulting closed-loop system from simulation result. On the other hand, designing an MRAC using the stability approach will ensure a stable closed-loop system based on observation from the above designs. The adjustable parameter θ_1 and θ_2 for Lyapunov method are simpler than that of the MIT rule.

The performance of MRAC designs depends on the adaptation gain, where the increase of adaptation gain from 0.5 to 100 will effect the above designs. It can be seen from Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6 , Figure, Figure 4.8, that although the controllers designed based on both Gradient/MIT and Lyapunov Methods respectively perform very well with γ of amplitude 0.5 when the amplitude of γ is changed to 100, the Gradient/MIT Method does not give very satisfactory results as the overshoots during transient is very high. This could result in the control actuator having to work extra hard at every cycle. The Simulink model shown in Figure 3.13 of (MRAC) is used to carry out simulation studies and analyze the performance of the controllers under different operating conditions.

5.1 Open-Loop Response of The Glass Melting Furnace System

The open-loop response of the model is shown in the Figure below. The Step-responses of the linearized model is continuously increased which means it does not get settled, unstable and not at the desired value. there is the need for a closed-loop system with a controller to control the value at the desired value and settle the output in a short time with minimum overshoot.

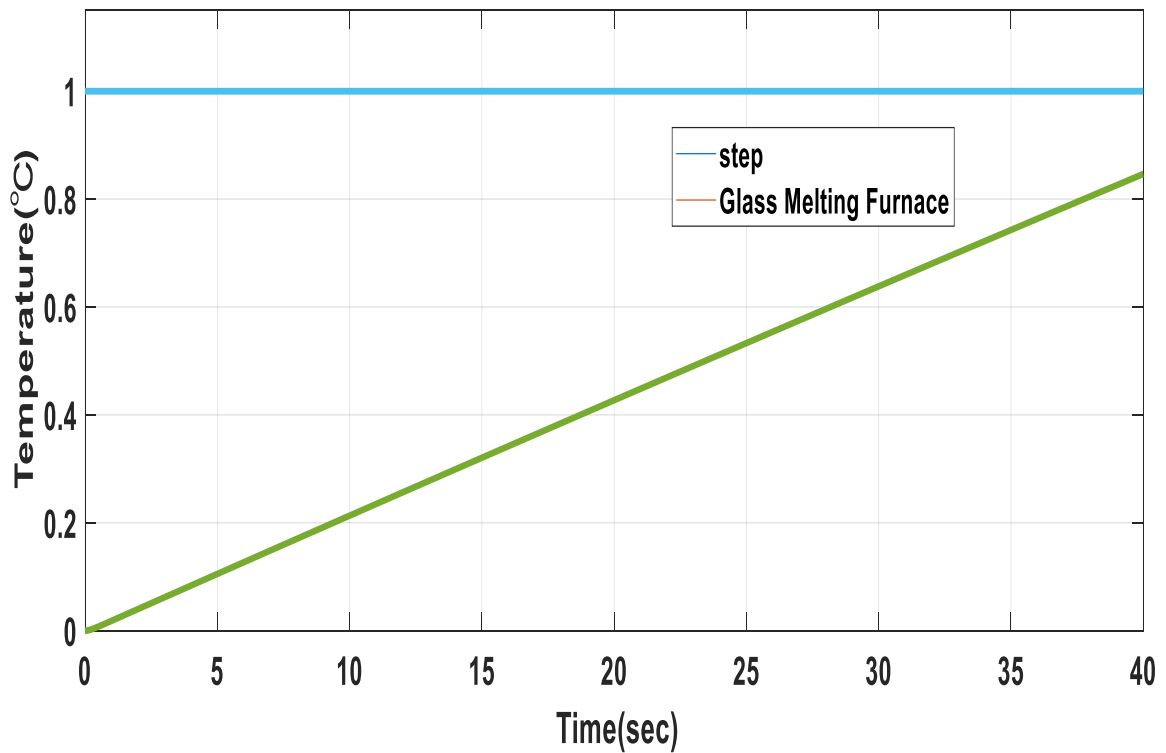


Figure 5.1 Open-loop Step Response of the glass melting furnace system °C

5.2 Simulation of PID Controller

The simulation result of the closed-loop system step response of continuous-time controllers is shown in Figure 5.2. For the continuous-time controller, the process and the sensor transfer function are changed to their equivalent continuous form for the simulation study.

The step response of the closed-loop system with a PID controller is shown in Figure 5.2. In this thesis the PID controller gains are tuned automatically for different ranges of robustness.

As it is observed from the Figure 5.2, with the MATLAB/Simulink PID tuned controller the step response of the system gets decreased in percent overshoot & settling time, increased in rising time and the steady-state error is zero. According to the design specifications, the allowable steady-state error is $\pm 5\%$. Therefore, the designed controller has met the desired specifications.

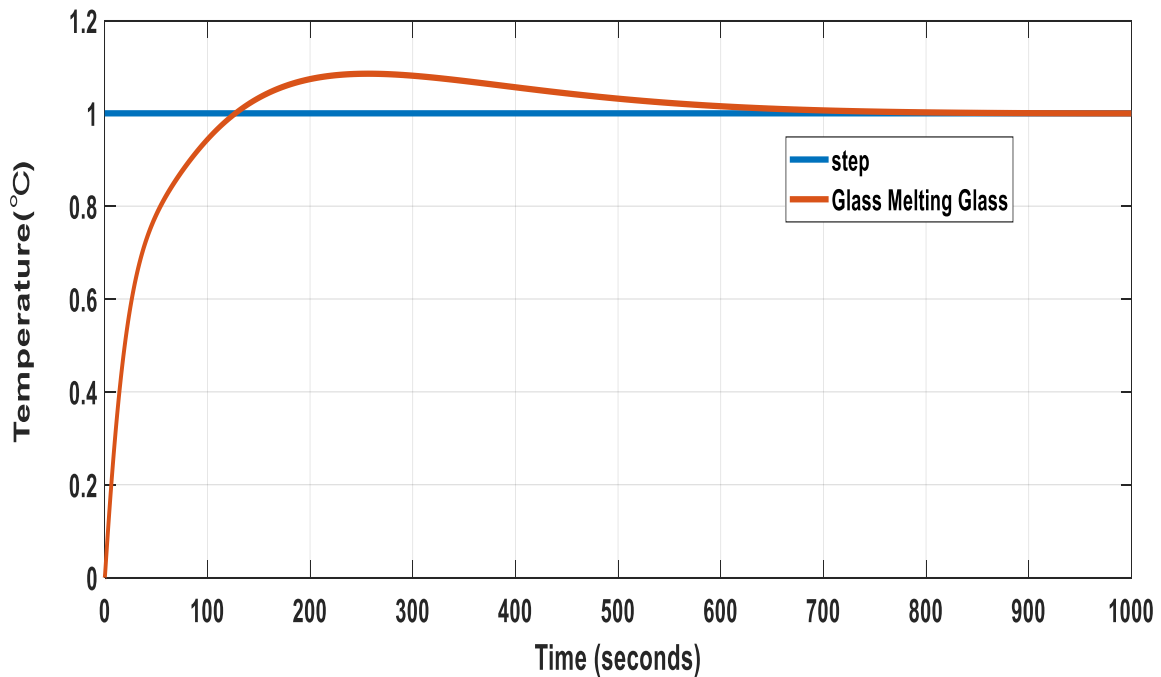


Figure5. 2Closed loop response of the Glass melting furnace control using PID controller

5.3 Simulations for MRAC System

Figure5.1 that it does not guarantee stability to the resulting closed-loop system. On the other hand, designing an MRAC using the stability approach will ensure a stable closed-loop system. The adjustable parameter θ_1 and θ_2 for Lyapunov method are simpler than that of the Gradient/MIT rule. The parameters are adjusted for MIT and Lyapunov controlling methods.

5.3.1 Results using MRAC based on MIT rule

In this thesis, the MRAC approach is applied to a furnace system with Gradient/MIT rule and the simulation results are shown below. Figure (5.3) shows the response of the actual plant and the reference model for different values of adaptation gain γ . Table (5.1) summarizes the dynamic behavior of the system in terms of time-domain parameters for various values of γ . It is clear from Figure (5.4) that, for large values of γ system responses fast with larger overshoots and for small values of γ system responses slow with small overshoot. In this thesis, the span of gain γ is chosen from 0.5 to 50 for the given system. Beyond this span, the system performance is not satisfactory.

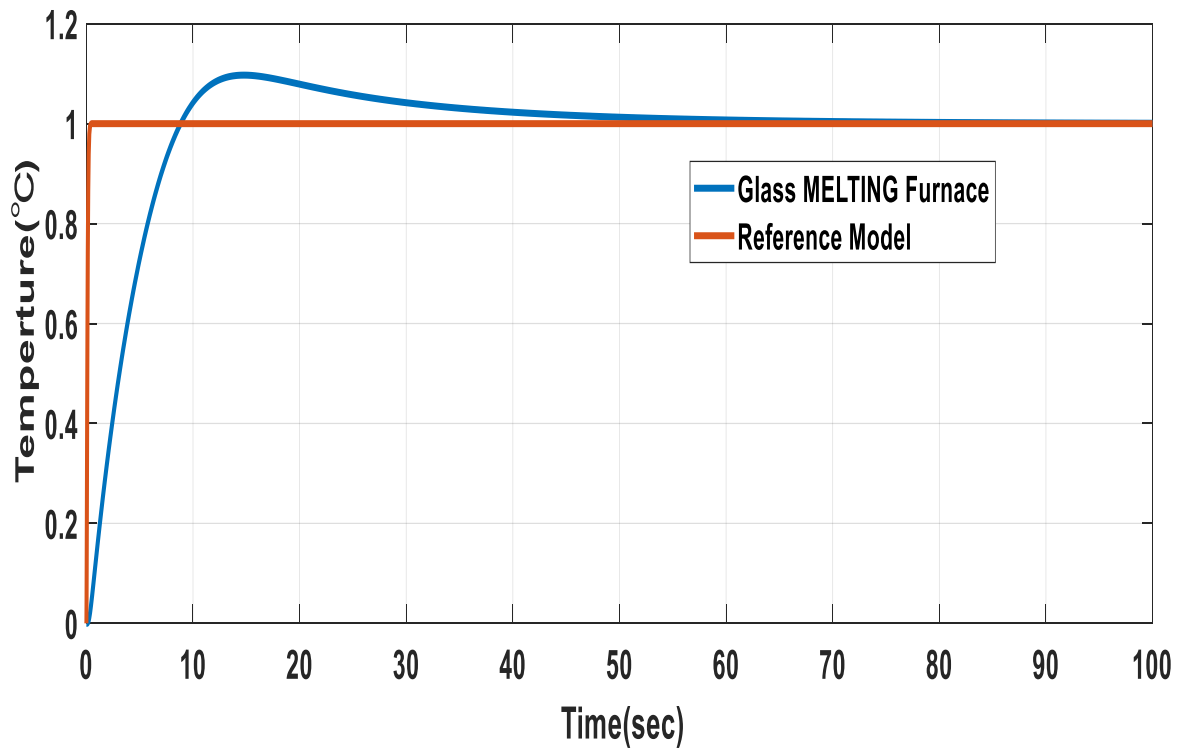


Figure 5.3 Simulations Result of MRAC with MIT rule and γ is chosen 0.5

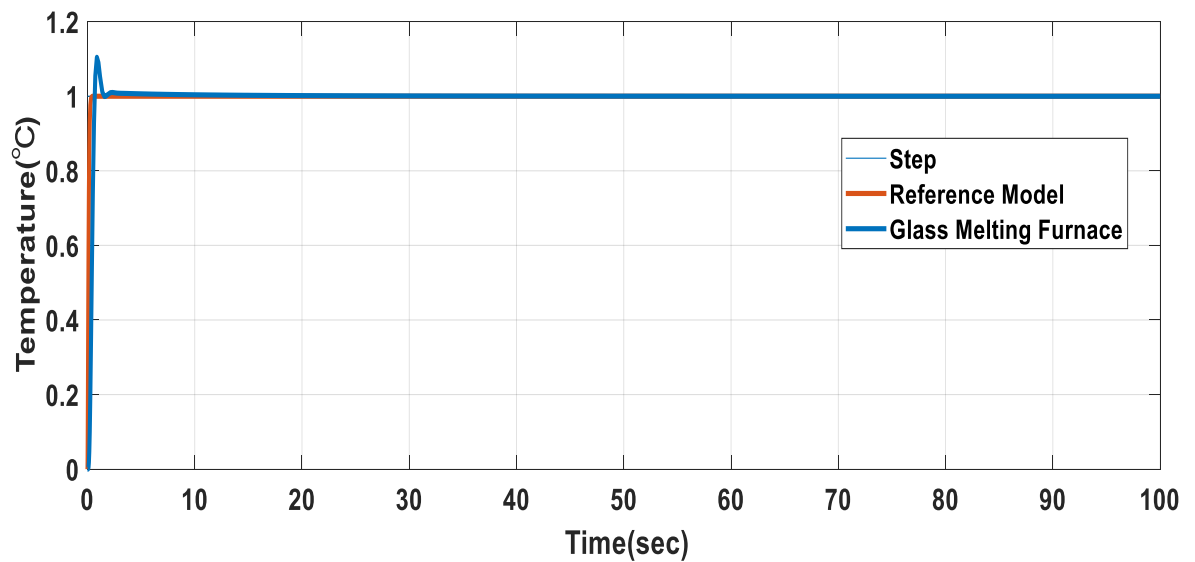


Figure 5.4 Simulations Result of MRAC with MIT rule and γ is chosen 10

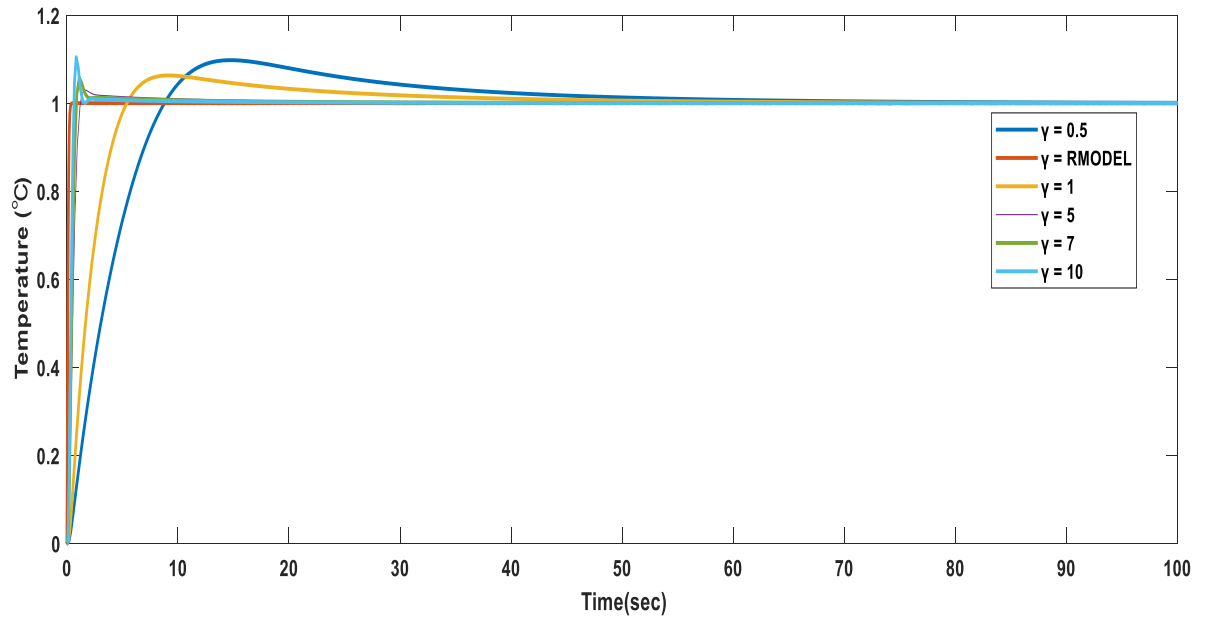


Figure5. 2 Simulations Results of MRAC with MIT rule and γ is chosen from 0.5 to 10

5.3.2 Results using Model Reference Adaptive Control Based on Lyapunov Rule

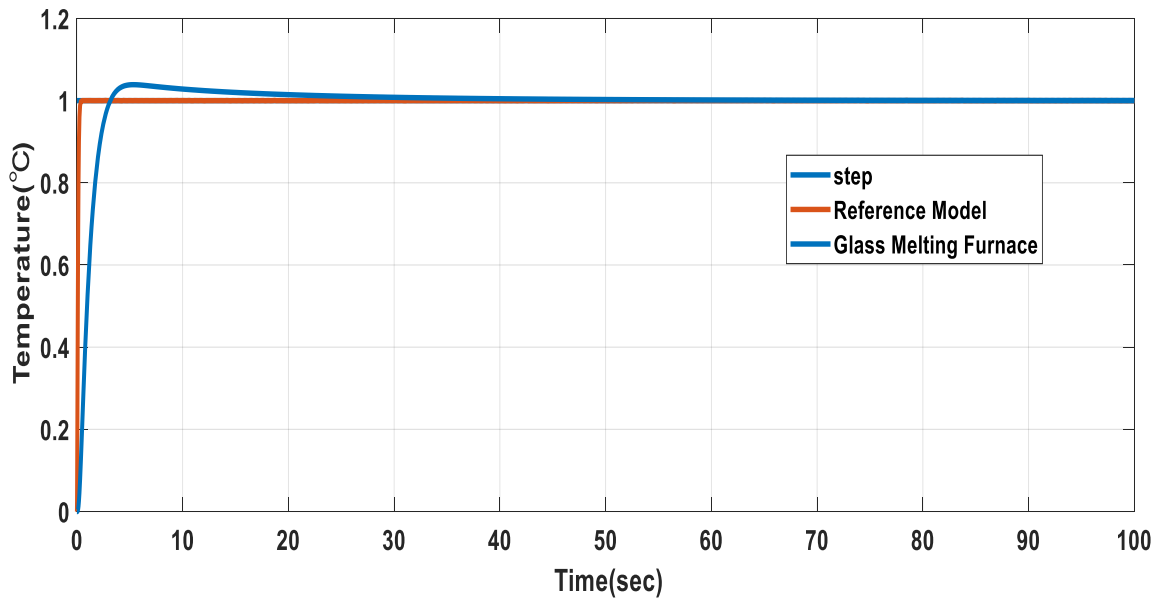


Figure5. 3 Simulations Results of MRAC with Lyapunov rule the span of gain γ is chosen 0.5

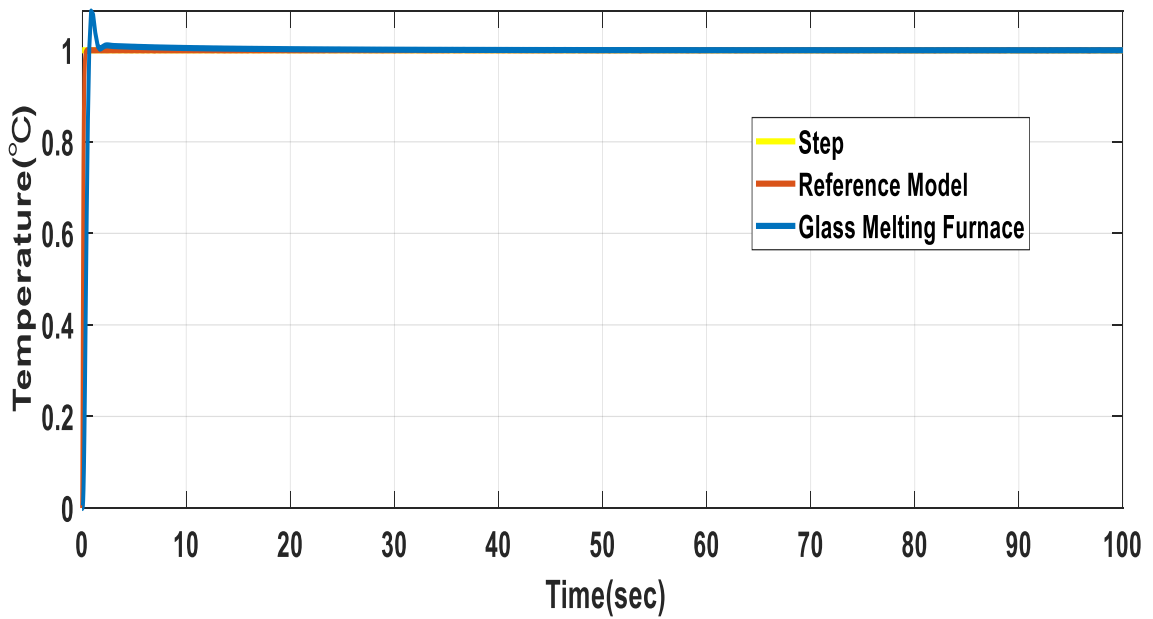


Figure5. 4Simulations Result of MRAC with Lyapunov rule and γ is chosen 10

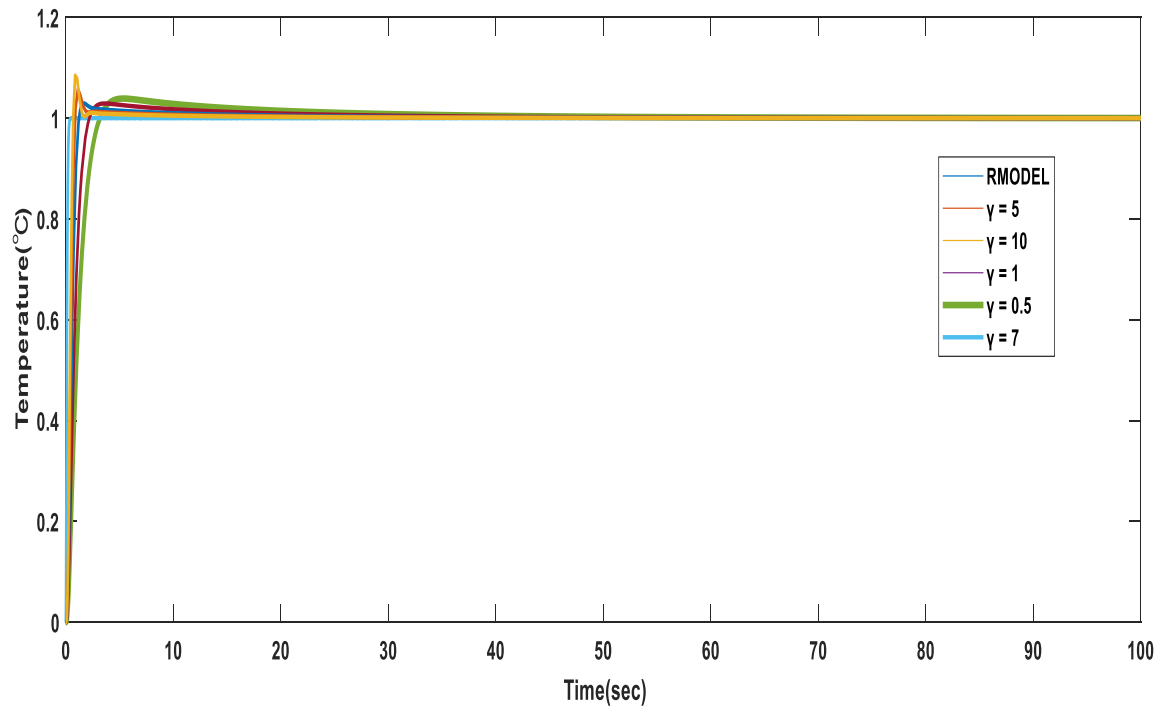


Figure5. 5Simulations Results of MRAC with Lyapunov rule and γ is chosen from 0.5 up to 10

Table 5. 1 Performance Characteristics Comparison of PID and MRAC Controller for Glass Melting Furnace.

Performance Characteristic	MRAC based MIT	MRAC based Lyapunov	PID
Over Shoot	7.4%	6.7%	10%
Setting Time	3sec	2.3sec	650sec
Rise Time	1.6sec	1.2sec	120sec
stability	stable	stable	stable

CHAPTER SIX

Conclusion and Recommendations

6.1 Conclusions

In this thesis MRAC with Temperature control of the glass melting furnace is designed. The furnace is a nonlinear and time-varying complex system. After proper assumptions and approximations are made to linearize the mathematical equations describing the furnace, the transfer function is obtained in the time domain.

The design procedure consists of 4 steps: First, mathematical model is linearized using Taylor series expansion on the selected operating points. Second, the PID controller is designed for model systems to compare with MRAC. Third, MRAC with MIT and Lyapunov rule adaptation mechanism is developed. Finally, the results obtained by the three controllers were compared where the automatic tuning procedure was followed for PID while the same values of gain were used for MIT and Lyapunov rules under different operating conditions.

A model that represents the glass melting furnace was developed. The performance of the MRAC and PID controller is tested through simulation studies using MATLAB/Simulink. It is observed from Figures representing the simulation results of MRAC that the response of the system improves with the increment in adaptation gain but beyond a certain limit ($10 > \gamma > 0.5$) the performance of the system becomes very poor. The selection of adaptation gain is very important and depends on the signal levels. The normalized algorithm, used in this thesis, is less sensitive even for very large and very small amplitudes of reference input. Therefore, it is shown that for suitable values of adaptation gain, the MIT rule and Lyapunov with normalization can make the plant to follow the model as accurately as possible.

Base on the results, the traditional PID temperature controller is not satisfactory to the higher degree of accuracy condition. Under MRAC the performance characteristics of systems are greatly improved and give better results regarding performance specification criteria. All performance specifications are good with fast rise time, short settling time and small overshoot. The system is also stable with around zero steady-state error. In general, the expected result from

MIT and Lyapunov rule-based MRAC is achieved successfully even though Lyapunov rule gives better results than MIT rule.

6.2 Recommendation

For the MRAC system, the adaptation can be optimized with a genetic algorithm for further improvements in the performance of temperature control of the glass melting furnace process rather than altering the adjustment gain by hand. Moreover, the hardware of the self-tuning MRAC and PID controller can be developed for temperature control of the glass melting furnace. As future work, since the dynamic model is available, without linearizing the system performance can be further improved by using a more advanced controller like an artificial neural network.

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