

**THESIS ON DESIGN OF OPTIMAL TEMPERATURE CONTROLLER FOR INCUBATOR
SYSTEM USING MODEL PREDICTIVE CONTROL**

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**THE THESIS SUBMITTED TO THE
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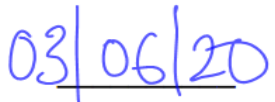
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I declare that this study entitled “Design of optimal temperature controller for incubator system using model predictive control” is carried out by me and only me independently except for the guidance and suggestions of the thesis advisor Dr.-Ing. Gebremichael Te-ame the thesis was not submitted for any other degree or diploma in this or other university by any other person so far. I also declare that I have fully acknowledged all the sources used and I have not committed plagiarism in any form.

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ABSTRACT

This thesis presents the design of an optimal temperature controller for an egg incubator system using model predictive control. Egg incubation is a technology that plays an important role in modern agricultural practice by providing temperature at an optimal level. The mathematical model of an egg incubator developed in this thesis uses the laws of conservation of heat and mass. A Linear Quadratic Regulator (LQR) algorithm is used to design the model predictive control (MPC) to control the egg incubator system that utilizes an explicit process model to predict the future response of an egg incubator system. At each control interval, an MPC procedure attempts to optimize future temperature of the egg incubator system behavior by computing the sequence of future manipulated variable adjustments. The basic MPC controller for an egg incubator system could be designed with a proper limit on the prediction horizon and model length. Also in this thesis, the prediction horizon must be kept sufficiently larger than the control horizon. The MATLAB™ software has been used to assess and simulate the overall behavior of the optimal temperature control of an egg incubator system parameters. The simulation results show that the optimal thermal factors are achieved when the egg temperature remains in the range between 36 - 38°C throughout the incubation period when using an egg incubator. Finally, the thesis was completed with simulation results, conclusions, and recommendations.

Keywords

Incubator, MPC, Optimization, LQR; temperature controller, incubation, modelling

LIST OF ABBREVIATION AND ACRIMONY

MPC	Model predictive control
DMPC	Discrete model predictive control
LQR	Linear quadratic regulator
PID	Proportional integral derivative controller
LQ	Linear quadratic
CO (CO ₂)	Carbon monoxide or carbon dioxide
CEI	Commercial egg incubator
RH	Relative humidity
LQG	Linear quadratic Gaussian regulator
LQE	Linear quadratic estimator
MIMO	Multiple input multiple outputs
LP	Linear programming
EST	Eggshell temperature
T_0	Steady-state temperature of outlet air, °C
T_i	Steady-state temperature of inlet air, °C
T_w	mean wall temperature of incubator, °C
T_i	Steady-state heat input, W
C_o	The capacitance of the air contained in heating chamber, J/K
C_w	Lumped capacitance of the structure J/K
K_f	Conductance ascribed to ventilation W/K
K_i	Conductance between the enclosed air and structure node, W/K
K_o	Conductance between the structure node and the outside air, W/K
K_e	conductance of egg (W/K)
Q_{emb}	Embryonic heat production
W /K	Watt per kelvin
J/K	Joule per kelvin

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CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

Incubator is the device that used to grow and maintain the cell culture. An incubator is device used to maintain environmental conditions suitable for hatching egg. It was the technology which play important role in modern agricultural practice. Egg evolution means technology which provide the chance for farmers to yield chicks from egg without necessity of mother hen. It is also one of the method to convert the egg into chicken. In commercial production of poultry products such as meat and eggs, a guaranteed sufficient supply of chicks was essential for market demand. The development of a new technology for a more efficient hatching of the fertile eggs are important. Egg incubators are widely used in the agricultural industry to control and provide hatching process under optimum environmental conditions. This optimum condition are temperature, egg turning, humidity, CO (CO₂) and oxygen content of the atmosphere inside of the egg incubator to stimulate embryonic growth until hatching.

The first incubating device was developed in 1857 by warmwännaen. In 1833 Pierre Victor Adolph was published other incubator which was settled by Etienne Stephane Tarnier for use of massive Paris Maternite called couveuse. The function of egg incubator was used to take over the animal job to incubate an egg until hatching. It is one of the easiest and fastest way that can increase the production of chicken. Hatching eggs were exposed to the various climatic conditions during the production, storage, incubation and hatching. The climatic condition in the respective stages of incubation can affect embryo development and hatching result [1, 18].

The development of new technology for more efficient hatching of fertile eggs is important. Poultry egg incubation can be done either by natural or industrial incubation. Natural incubation of chicken eggs given that the home to heat and control humidity and also turned on from time to time. The temperature and relative humidity (RH) inside the incubator must be controlled to optimum environmental conditions in the range of 36-39°C and RH of 60-80% [15]. The incubating temperature is the most crucial factor in incubating efficiency [6, 18]. In case of the commercial egg incubator system (CEI), the heating element was used as heat source by directly converting electricity to thermal energy.

Optimum incubation temperatures were defined as the determining of egg shell temperature of descriptive sample of eggs randomly selected from diverse plates in the incubator. Egg shell temperature was determined by mixture of the metabolic heat produced by embryos and the climate energy (temperature, air flow, humidity) bounded the eggs. In this way, a new kind of egg incubator system should be researched which could be self-adaptive for the change in the environmental temperature control using MPC for the egg to be hatches. Therefore there are several control techniques of optimal adaptive control system. These are gain scheduling and model predictive techniques. In this thesis, model predictive controller was designed to solve the problem of temperature of an incubator system at optimal or safe operation level.

1.2. JUSTIFICATION

Majority of Ethiopian farmer has little (no) knowledge of programmatic or computer control. Generally, environmental factors like humidity, turning time, temperature affect the formation of medium to large scale poultry production suits in both pastoral and urban areas of the Ethiopia. Based on this obstruction, there was requirement to do additional studies on automatic control for self-regulation so as to provide optimal temperature for hatching purpose. MPC has advantage over most classical control system and it is handles multivariable constraints. This thesis will not restrict our discussion to the basic algorithm and practical considerations. This includes offset free tracking set point and regulation, and only touch upon some theoretical issues like nominal stability.

1.3. PROBLEM OF STATEMENT

Chicken is one of the endemic bird that pastoralist uses for both foods and source income. The most commonly used temperature both for the egg prison cell were around 37 °C (99 °F) and these organisms grow well under such conditions. This was used in cultivation of egg cells where the relative humidity was typically greater than 80% to prevent evaporation and slightly acidic pH was achieved by maintain CO₂ level at 5%. In the early phase of embryonic expansion of little metabolic temperature was formed and the air surrounding the eggs should be excited to keep the egg shell temperature at most favorable levels. It was used in temperature for hybridization, but due to the uncertain environment (unbalance temperature and humidity) of the egg gets risk of damage.

When the hen hatches its egg, the hatching process may not be successful due to variety of problems and also the hen has not power to hatch lot of egg at one time. But towards the end of maturation, the production of metabolic heat increases and this heat must be removed by cooled air flowing over the eggs to avoid the risk of overheating the developing embryos. If the energy loss was not stopped and permitted to continue, the egg was develop hypothermia or low body temperature. This increase risk of health problem and even death for the case human baby. The reason that the temperature cannot be lower than the 36°C, because the embryos in the eggs may not develop properly and may have underdeveloped internal organs when they hatch.

Optimal warm air circumstances motivation be reached when the temperature rests in operation temperature range and both oxygen consumption (heat production due to the metabolic activities) and insensible water losses (the heat loss due to evaporation, conduction, convection and radiation) are at minimum levels. If fertile egg start again development of maturity, then it was located in egg incubator and the mentioned temperature for maturation changes in the range of 36-39°C without affect its development. Therefore, the problem of optimal condition of egg incubator was improved by designing MPC or model predictive control.

1.4 OBJECTIVES OF THE THESIS

1.4.1 GENERAL OBJECTIVES

The main objective of this thesis is to design of temperature controller for egg incubator system by using model predictive control.

1.4.2 SPECIFIC OBJECTIVE

The main specific objective of the thesis were listed as follows:

- To develop mathematical model of the incubator system
- To design an MPC controller
- Checking the stability of plant under MPC controller
- To test and evaluate the obtained model by using MPC on the MATLAB™
- To compare the performance of MPC with PID controller.

1.5. METHODOLOGY

To have full information and an insight about the thesis and its nature, the study starts with reviewing the literatures related to the temperature control of an egg incubator system. Recent published journals, some books concerning the egg incubator system and unpublished documents will be investigated in this work. General methodology for this thesis work includes the following and for the purpose of analysis data from the following offices will be collected:

- Interviewing experts and professionals at the poultry agriculture would be conducted.
- Recorded data and existing information for the assessment will be considered to come up with a clear solution for the stated problems.
- The collected data from above mentioned areas and from the field work have been analyzed and a model temperature control of an egg incubator system by using MPC for poultry agriculture is designed.
- Gathering data from ministry of Agriculture and poultry industry of Hawassa and around A.A to get relevant national standards and current updated information related to this research work.
- The data's on the egg incubator technicians operation and maintenance system gathered.

- Analysis of technical and economic performances and analytical methods based on mathematical models are used to solve performance of the system.
- The law of conservation of energy was used to develop physical model.
- Finally, model of incubator system was designed based on the analysis result so as to improve its performance.
- We use LQR for optimization, model predictive control techniques for adaption.
- Software will be used to assess and simulate the overall behavior of the temperature control of an egg incubator system and we use MATLAB™ Simulink's for testing the objectives.

1.6. SCOPE AND LIMITATION

1.6.1. SCOPE OF THE THESIS

This thesis was limited for the temperature control of egg incubator using MPC. The temperature control of an incubator system analysis of egg for hen/chicken with optimally controlled temperature by designing MPC.

1.6.2. LIMITATION OF THESIS

When conducting this thesis practically faced different limitation including difficulty of getting data, design mathematical modeling and returned as the planned time. In addition to this the time and budget were major constraints to limit this thesis. Moreover, the thesis was conducted on the one of the stage egg incubator and does not cover the whole stage.

1.7. SIGNIFICANCE OF THE STUDY

The thesis would contribute as an input for academics knowledge of the practical interlink for optimal temperature control of an egg incubator using MPC based on the theoretical literatures written on this topic. The thesis conducted by this study used for ministry of agriculture of Ethiopia in general and to those who are interested to conduct such thesis in particular considered to be essential because it could provide information about the government of Ethiopia has been hard working to bring changes in the country in its own long term strategic plan. Among the activities, industrializing the agriculture, building new dams, strengthening and expanding electric power to supply for urban and rural dwellers. So, it was one of invention that provide opportunity to industrialization of agricultural sector for whom want to be an excellent farmer and people who

live in urban. So, controlling temperature of an egg incubator at optimal level gives the right condition to hatch hens/chickens. Furthermore, this study gives opportunities for famers those who live in rural and urban areas to focus their attention on poultry farm. It also proceeds portion of industrialization agricultural sector which was settle the mechanism that varies as technology transfer. The design used to generate highest output with lowest budget economies scales. Therefore, main contribution this thesis provides the chance to modern farmer to enhance their products by design of optimal temperature controller for egg incubator system using model predictive control.

1.8. THESIS OUTLINE

This thesis was consist six chapters which include the Introduction, Literature Review, Methodology and the rest of the thesis is organized as follows:

Chapter two consist the literature review which includes the main components, factors that affect, incubation conditions, typical values used for the egg incubator and history of MPC. Chapter three explains about the methodologies of the thesis which consists of system modeling for temperature control, conceptual design of the incubator based on the mathematical model. Chapter four discusses all about the controller design MPC controller. Chapter five discusses about the end result and discussion. Finally chapter six draw conclusion and recommendation of the thesis. At the end of thesis appendix and reference attached.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 INTRODUCTION

Incubation was the hatching practice of birds their offspring and development of embryo with in the egg incubator system. The most vital factor of incubation was to maintain a fixed temperature required for its development over the specified periods. In most species body heat from brooding family runs with fixed temperature. Also humidity was unsafe if air excessively dry egg, which lead much water lose to the atmosphere which could make hatching difficult. If the egg would in general lighter and the air space with in egg would also normally larger own to evaporated. If maturity of egg organs occur in the later phases of embryonic development, these phases were require the exact egg incubator system environmental situations [1].

According to Michael. H. Le Blanc [2] studied on, Thermo-regulation incubator radiant warmer at the artificial skin and body egg. Keeping egg warm whether use incubator or radiant warmer was important to optimize the chance of survival. The history of an egg incubator and the lesson derived from discussion of the basic thermoregulation and available data regarding the use egg incubator and radiant warmer as well as thermoregulatory devices. The first practice of incubator for upkeep of early infant/egg was in 1722. Trainer (Parisian obstetrician) [2] adopt the idea of using egg incubator for the care of premature egg/infant. Meanwhile that period the incubator industry observed the great development and by 1896 the basic arrangement of the incubator system design was accomplished and still practice the basis of today egg incubator.

According to Gerald B.et al, Radiant heater were relatively new and used for nursing ill infant with very little birth weight later 1969 [3]. Many study has illustrated the existence degree of low birth weight infant favored in incubator system or under radiant warmer greater than before and the warmer environment situations were delivered.

Furthermore to this the drawback of PID controller used to find true parameter, compensate the plant delay and making plant stability study was completed. It is used to confirm a suitable environment for the early born infant or egg using advanced control system policy and keep output temperature without significant change over the period of time [5].

Mahmoud Salim considered "Design and Implementation of Digital Control Unit for Oxygen air Servo Baby Incubator" the system was need automatic control of temperature and humidity for different types of eggs or infants. The function of egg incubator was used to incubate egg until hatching by replacing hens jobs. Now a day there are many sensors like thermocouple, thermistor, liquid thermometer and bimetallic strip were available in the market to measure the desired temperature. It was used to monitor and control the light and oxygen level in the incubator system [6]. The egg (infant) has very low thermal regulation and temperature regulation was the most important factor which can affect the preterm [12].

D. L. Miller, et al, considered as the skin temperature in the instantaneous neonatal period, the effect decrease warm air loss. The optimal thermal condition was accomplished if the skin temperature stay in the range of 36.8 - 37.2 °C [14] and both oxygen consumption (heat production) and insensible water losses (heat loss) are at lowest levels. There are various type of egg incubators like open box, close box type, manually controlled, servo controlled and transport incubator.

The egg incubator system was meet multiple problems in operative environment. The first challenge was changing physical model of incubator system as the cause of relations between early egg and its atmosphere. Other problem was an outside disturbance [17, 18] in line for to the opening of the right to use gate throughout the medicinal intervention.

J. Dostál* L. Ferkl*, considered as the Model Predictive Control of Climatic Chamber with On-off Actuators. In this paper the only open loop was simulated. Beside the condensation process, the dynamics was linear in all variables so the linear model of chamber was developed using subspace state space system identification algorithm. The Climatic chamber, energy consumption and humidity controlling of the chamber with on-off actuator by only switching MPC [28].

The primary study of this thesis was computing mathematical model of an egg incubator system to control its temperature at optimal level. For simulation this model used to predict the future temperature continuously by designing the Model Predictive Control (MPC). The model of egg incubator system was consider predict the past and future behavior of temperature of egg incubator over the time frame. Therefore, in this thesis the problem of the operating temperature will be calculated using MPC. Also this model uses wide range of stimuli, the transient and steady state behavior. This thesis enabled us to find the real parameters of modeling. Generally, this thesis assess the major constraints that can influence by design the optimal temperature controller for egg incubator system using MPC controller.

2.2. FACTOR AFFECTS THE PERFORMANCES OF EGG INCUBATOR SYSTEM

2.2.1. TEMPERATURE

The fertile egg start again the development when positioned in the incubator system and the suggested temperature for maturation changes with range of 99-103°F without special effects. If temperature stay extreme for numerous days, the hatch might be minimized. The hotness was much more serious than under-heating, it would speed up degree of the development which cause abnormal embryo development in the premature phases and lower percentage of hatchability [7].

2.2.2. HUMIDITY

Humidity have abundant importance for development of chicken that were started from their embryonic stage. During the maturation or embryonic development, the humidity was absent from the egg through little hole on the egg shell. This growths the dimension of the air cell which later 19 days of maturation occupied about one-third of the egg, while the change of 5 to 10% was suitable. The relative humidity of the air with in the incubator system for the egg first 18 days should be 60% during last 3 days or the matching time was near to 70%. When humidity was lower than suggested value it cause extra evaporation of water, while the high humidity was prevented evaporation of adequate amount water from the egg.

2.2.3. TURNING OF EGGS

While eggs were position in an egg incubator system, lay them on their sides and turn them at least three times in a day. Rotating the egg was prevent the embryo from sticking to the shell membrane, if it was left in one position too long. Better results could be obtained by turning egg in the morning, at afternoon and evening times. It was better to turn egg more than three times within day and it should be rotated odd number of at time. So the egg would not be at the same level every evening, because it was the extensive time between turns. Uncertainty turn the egg, now the egg move to various part of tray with offset difference of temperature of egg incubator system. Turn the egg day 2 complete day 17, then subsequently day 17 turn was not essential.

.

2.2.4. EMBRYONIC DEVELOPMENT

Early development was endless procedure which consists three different stages. These stages were variation, growth and evolution. Variation of the body part occur in first days of maturation period. The growth and evolution of body part occur in the later phases of development. Each of these stages need exact egg incubator system situations. As the embryo grow, its metabolic rate rise and it was accomplished by increase the temperature creation.

Accordingly, the normal shape of the embryo and eggshell temperature show rise end of the maturation. In the egg incubator system change temperature in the middle of set-point on which egg incubator system work and temperature of air at level of egg was determined temperature of egg and embryo [2]. Next to start of maturation the embryo was yield little temperature and eggs should be warmed. This means air temperature might be higher than egg shell temperature. For instance the embryo grow, metabolic rate and temperature production were increased to prevent over-heating air enclosed the egg for cooling purpose. Although this temperature not completely uniform, it fluctuates slightly between various parts of body. For practical reason the assumed temperature distribution between various parts of body and embryo was uniform. As egg shell loss heat, there was temperature increment between body of embryo and egg shell.

2.2.5. FERTILE EGG QUALITY

After the minor canary egg to major ostrich egg, the high quality fertile egg would be measured as infrequent and breakable. Just before effectively hatch the egg arise with fresh, clean and fertile egg. The egg could be produced on site or bought from other places. Marketable hatchery could confirm good fertility, but often could not ship small quantity of egg.

2.2.6. STORING FERTILE EGGS

The egg hold living cell form developed into embryo and finally to a chick. This occurrence of the unsuitable treatment was reduced chance of effective hatch. Fertile eggs were usually collected over the period of time before adequate number of the eggs could accumulated for evolution or until the incubator was available for new set of eggs. These regular circumstances required before incubation and the egg might be stored for proper hatchability.

2.2.7. CLEANING AND CULLING

The cracked and soiled egg had better not be incubated. If the egg hatch increase chance of presenting infection into the egg incubator system, then egg should not be washed. The washing or wiping with damp cloth remove protective layer that cover the egg. The soiled egg should be cleaned by gently buffing soiled area of egg with fine sand paper. The washing egg transmission disease contamination agent from chamber to inside of the egg. If eggs were washed in 110°F water that contains the marketable sanitizer. The contraction of the egg draw water into egg through pore in the egg shell. This water might be transmit infected microorganism into the egg. If fertile egg were produced on site, the breeding stock must be maintained and sustained extreme health and fertility. Basic egg production was affected by day length and lighting control.

2.2.8. FUMIGATION

It was technique were conventionally used for the agrarian application and gas control measure in egg incubator system. Because of this mechanism affect structure that egg inhabited the arrangement were suffocated to death. Fumigation was operation which destroys organisms that might be killed embryo or the chick by exposing the organism to poisonous gas.

2.2.9. STORAGE TIME

Perfectly, the egg should be placed in egg incubator as rapidly later collecting as possible to keep its quality. If it was to be stored before maturation, the best hatchability occurs when it was stored for less than 7 days from the time hens were laid. Hatchability decreases rapidly, the eggs were held in storage more than 10 days. Storing egg more than 2 weeks, it spreads regular evolution time as much as 1 day.

2.3 INCUBATING CONDITIONS

The reduced result was most frequently formed with incorrect control of temperature or humidity. Incorrect control means that the temperature or humidity is excessively high or excessively low for the enough length of time that obstructs with a normal growth and enlargement of the embryo. Poor results also occur from incorrect air circulation, egg turning and hygiene of the machine or egg.

The parameter had better control the egg incubator system like temperature, humidity and ventilation. The temperature should be influenced by the type of egg. In order to hatch a respectable percentage of fertile egg, incubator should be able to keep fixed temperature. Though different sorts of eggs need dissimilar heat levels, most stimulus to grow and hatch in good health at 99 to 101°F. Sure that does sound imposingly more exact, but such accuracy was not all that challenging to accomplish [5]. Infrequently, the humidity excessively high in properly ventilated still-air incubator. The water pan area should be corresponding to the one-half the floor surface area or more. Enlarged ventilation during the last a small number of days of maturation and hatching might be necessitated the addition of extra pan of the water or a wet sponge. Then the humidity was preserved by increasing the unprotected water surface area.

However the embryo was developed, the oxygen moves in through the egg shell and carbon dioxide released in the same manner. As the chicks hatch, they need to increased supply of fresh oxygen. Such as embryos grow, the air vent opening was progressively opened to satisfy better embryonic oxygen response. Care must be taken to keep humidity during the hatching period. Barred

ventilation holes, both above and below the eggs were essential for correct air conversation in the incubating chamber. As the embryo grows they uses oxygen and release carbon dioxide.

Overheating was much more serious than under-heating, because it would speed up rate of development by causing abnormal embryo development in early phases and lower the percentage of hatchability. If the eggs were too hot during incubation time, then there was better chance that they would die from over-heating that would cause them to die shortly after birth.

Despite the fact heat loss was evaporating, then there was heat loss (insensible water loss) and non-evaporative heat loss (including both the convective and radiative heat loss). This couldn't be achieved by natural incubation by means of a hen's body sitting on a clutch of egg. The current poultry, egg incubator face issue of heat loss due to poor approach of turning eggs and thermal insulation of the incubating chamber which lead to temperature variation and reduce hatchability of the egg.

Consequently, adequate ventilation with in egg incubator system was essential to settle the supply of oxygen and removal of carbon dioxide. The best hatching outcome were achieved 21% oxygen air, which was the normal oxygen level in the atmosphere and embryo would accept the carbon dioxide level of 5%. If the normal oxygen and carbon dioxide concentration existing in air to use represent best gaseous atmosphere for incubating eggs. Table 2.1 shows below that suitable temperature and humidity. The Fahrenheit unit could be converted to Celsius using Fahrenheit formula, $F = [32 + (9/5)] \text{ } ^\circ\text{C}$.

Table 2.1: Condition of the egg incubator system for different types of egg of various birds

Type of birds	Time or period of Incubation	Temperature in °F	Humidity in °F	Don't turn	Humidity last 3 day	Open vent
Chicken/hen	21	100	85-87	18 th day	90	18 th day
Turkey	28	99	84-86	25 th day	90	25 th day
Duck	28	100	85-86	25 th day	90	25 th day
Muscovy duck	35-37	100	85-86	31 th day	90	30 th day
Goose	28-34	99	86-88	25 th day	90	25 th day
Guinea fowl	28	100	85-87	25 th day	90	24 th day
Pheasant	23-28	100	86-88	21 th day	90	20 th day
Peafowl	28-30	99	84-86	25 th day	90	25 th day
Bobwhite quail	23-24	10	84-87	20 th day	90	20 th day

2.4 TYPICAL VALUES

The important typical parameter egg incubator system values were given as follows:

- Air temperature: 32 to 38°C.
- Skin temperature: 34 to 36°C.
- Total gas intake: 35 l/min.
- Relative humidity: 50-100%.

2.5 HISTORY AND EVOLUTION OF MPC

This section of thesis has introduced about the history and evolution of the Model Predictive Control in academia based concept of optimal control theory, which giving the birth to very first industrial based control applications using MPC technology. More comprehensive historical survey of industrial MPC was founded in the article Qin and Badgwell (2003). MPC were popularized in the late 1970s for the control of petroleum refinery operation, which was used to operate constraint on manipulated variable and controlled variable.

The development of modern control concept using the optimization method could be traced to early 1960's beginning with job of Kalman (1960a, b). The first attempt for optimal control of linear system was result the development of linear quadratic regulator (LQR), which was designed to optimize unconstrained objective function over the system state and input. The main asset of LQR and LQG controllers were powerful in stabilizing infinite horizon.

Yet, early practical issue control applications were massive in quantity, quality and influence on the industrial process control technology limit. Because of forgetting basic properties in its formulation like a constraint, the real system, nonlinearity, model uncertainty and unique objective criteria.

2.6. DESCRIPTION OF MODEL PREDICTIVE CONTROL SYSTEM

The overall system become described in the following in figure 2.1.

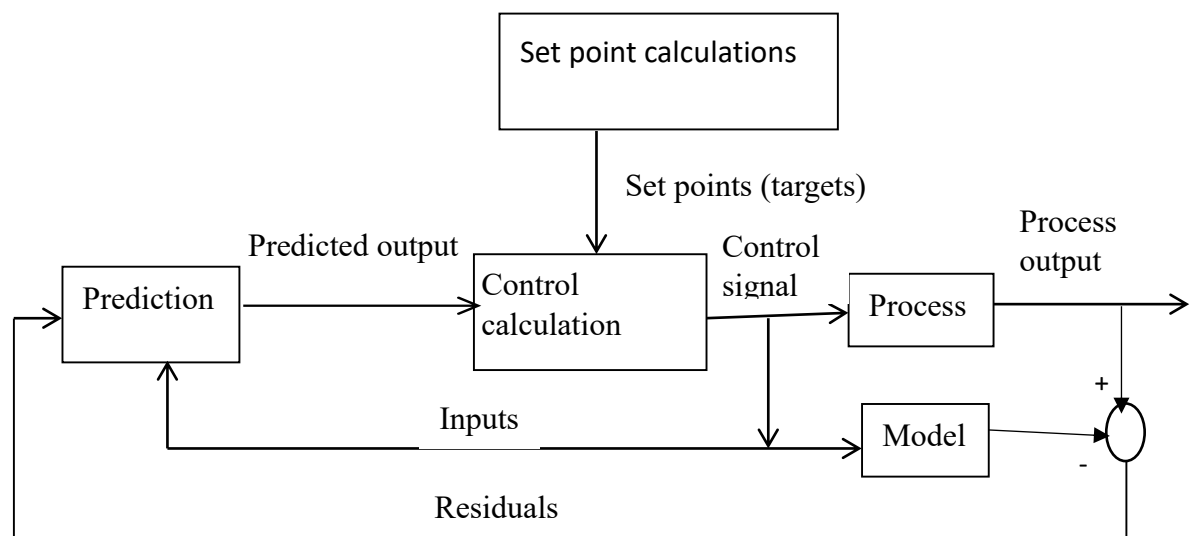


Figure 2.1 Basic block diagram of MPC of an egg incubator system

Process (egg incubator) model: is the model which was used to predict current temperature value as output variable. Model of the plant/egg incubator acts in parallel with process and residual.

Residual was the difference between the actual plant and predicted output and it acts as the feedback signal to prediction block or model predictive control (MPC).

Prediction: used in the set point calculations and control calculations. Inequality constraint is used in either type of calculations.

Set point: used in the control calculation and it is also called as target point. Set point calculations are usually based on linear steady state models and a simple objective functions. These calculations are repeated at each sampling instant because active constraints can change frequently due to disturbances.

Control calculations: were based on current measurement and prediction of the future values of the output.

Terminology: $y \leftrightarrow$ CV (controlled variable or temperature of egg incubator), $u \leftrightarrow$ MV (manipulated variable or control signal), $d \leftrightarrow$ DV (disturbance that affects the system).

2.6.1 COMMON FEATURES OF MPC

The MPC has good features and some of these are:-

- Model of system to be controlled.
- Criteria (objective or usually quadratic) function that to be minimized.
- Reference of system input and a minimization procedure.
- Also it calculates such future controller sequence that predicted output of system.

2.6.2. BENEFITS OF MPC

The benefits of the MPC are discussed as following points:-

- Minimize the operating cost while meeting constraint (optimization, economic).
- Superior for process with large number of manipulated and controlled variable.
- Allows constraint to be imposed for both MV and CV.
- The ability to operate closer to constraint, allow time delays.

CHAPTER 3

3. MATHEMATICAL MODELING

3.1 CONCEPTUAL DESIGN

The key component of egg incubator consists like compartment, regulator method and power supply. Automation was presented to decrease the need for human being interference in production of chick using the MPC controller system. In this thesis, the single phase egg incubator was designed, because all eggs in unit were set on the same phase of evolution. To insure better possible maturation, the important environmental factor like temperature, humidity, airflow and movement was needed. The hatching process done by keeping temperature at 37°C throughout incubation time or period. The minor variations (less than 0.5°C) above or below were 37.5°C accepted.

Air ventilation was played an important role in cooled overheated machine. The internal fan speed should be settled at 7200 rpm.

Positioning and turning: the common exercise in chicken was to settle the egg vertically with the air cell at top of the egg. At all egg were positioned on their side should be turned on their longer axis. This means the direction of egg were settle at angle of 45°, later the angle of 90° turn, then they challenged 45° the other direction. The measurement of system filing cabinet existed with size of 0.75×0.75×0.5 m.

Feed-back control of egg incubator manipulate input for egg incubator to reduce its error. The error produce in the egg incubator system due to output - desired output. The feed-back control of an egg incubator react to the egg incubator system and it works to reduce produced error. Then the desired output of the egg incubator system was generally entered into the system through a user interface. The egg incubator control by using MPC was basically a feedback control system. Feedback control was the basic mechanism of the egg incubator system, whether mechanical, electrical, or biological to maintain their environmental factor at equilibrium or homeostasis.

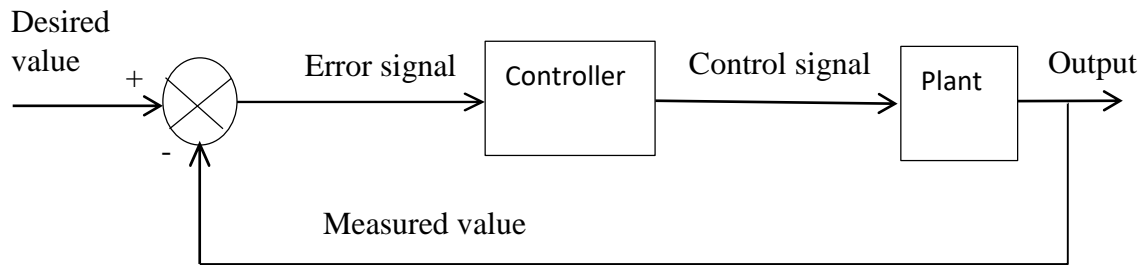


Figure 3.1 block diagram of closed loop/ feedback control system

3.2 SYSTEM MODELLING

3.2.1 PHYSICAL MODEL FOR INCUBATOR

The mathematical model of an egg incubator system was developed from its dynamic behavior. A model of an egg incubator system was also essential for gaining the deeper insight and understanding the overall systems. The goal of an egg incubator system analysis was used to predict the system's behavior under unforeseen circumstances, which used to determine how the change in the input to a dynamic system and its parameters affects its output. Therefore, the use of an egg incubator system models was not only justified, but crucial. The egg incubator system was deliver essential circumstance for fertile egg incubation from this most vital condition temperature was first one. The most favorable temperature for most egg incubator for hen/ chicken was around 37.5°C.

The analysis the model structure in Figure 3.2. below summarize the basic phenomena that occur in the egg incubator system were given as follow: these include convective energy transfer of egg incubator system with external air, the radiative transfer of egg incubator with the external air, the convective heat transfer of egg incubator with the internal air, the radiative heat transfer of egg incubator between the wall and heat transfer of conduction through completely mirror wall. This thesis began design of an egg incubator mathematical model by gathering information and analyzing by using the knowledge of the dynamic behavior of egg incubator system.

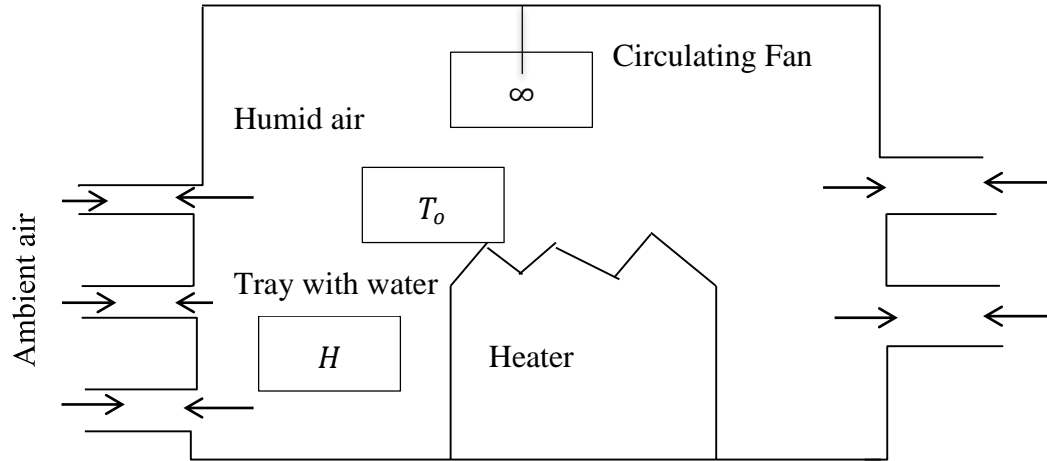


Figure 3.2: Physical model of an egg incubator representing all heat transfers

In the design, inlet ambient air at the temperature T_i of egg incubator was heated to the temperature T_o of egg incubator by using the supplying heat energy Q_i to the heater. The temperature T_o of egg incubator provide the necessary humidity and plate of water were settled inside the egg incubator system whose exposed surface area was adjusted to control the amount of humidity. In addition to this the output air temperature T_o of egg incubator, the internal egg temperature T_e are the other measured variable. The internal egg temperature T_e of an egg incubator system difficult to measure directly but it was approximated to the egg shell temperature which was the actually measure the parameter. Internal egg temperature T_e of an egg incubator system was influenced by T_o and internal heat of an egg incubator system Q_{emb} produced as the result of metabolic activities by the developing embryo. By the side of the start of evolution time, then degree of metabolism was low and Q_{emb} was small. At this stage, T_e was less than T_o , due to this the egg will be gaining heat from the surrounding air. However, during the next half of incubation time, the egg would lose heat as T_e increases above T_o .

3.2.2 BASIC ASSUMPTION

The basic assumptions for the development of the egg incubator model in this thesis were:-

- A section was assumed to be similar through its material.
- The air flow in the egg incubator system and air surface was uniform.
- All energy transmission was assumed two-way.

- The convective and radiative conversations were indicated by the factor of global heat transfer.
- The wall of incubator was modeled by balancing the conduction coefficient with resistor.

3.2.3 DYNAMIC HEAT BALANCE EQUATIONS OF EGG INCUBATOR

Like the most thermal systems, the egg incubator models are also complex system having many parameters. By using all these variables into account, in this thesis focuses the design the egg incubator model by using impractical approach. Therefore, the lumped-parameter of egg incubator model considered here was idealized representation of actual system dynamics. The lumped parameter of the egg incubator system models were based on the Newton's laws or general heat balance principle.

Assumption1:- The rate of change of the energy deposited in enclosed air was counter balanced by heat input and the heat transmission rate between the air and wall, between the air and environment and between the air and egg.

Assumption2:- The rate of change of energy packed in egg incubator wall equivalent to heat gain by the wall from enclosed air at temperature T_o , recompensed by temperature loss from wall to environment.

Assumption3:- Finally, the rate of change of energy deposited in the egg equivalent to summation of heat gain of egg or heat loss from egg, if egg was warmer than enclosed air and heat added due to embryonic heat production Q_{emb} . By using this assumption the mathematical model developed. The number of assumption has been made based on the above derivation of the lumped parameter of egg incubator model presented here: -

1. Temperature distribution inside the egg incubator was uniform, this implies that the constancy of such properties as density and specific heat capacity of air.
2. Temperature distribution throughout the egg was homogeneous.
3. Every single egg was exclusively bounded by air.
4. There was not at all instantaneous change of speed of air in egg incubator system.

Finally the (3.1) below, which was derived based on the principle of preservation of mass and on fundamental of heat transmission laws, the dynamic heat balance equation of an egg incubator system were developed. So, the following (3.1.a), (3, 1.b) and (3.1.c) were derived from the above basic assumptions 1, 2 and 3 respectively, as stated above:

$$C_o \frac{dT_o}{dt} = Q_i - K_i(T_o - T_w) - K_f(T_o - T_i) - K_e(T_o - T_e) \quad (3.1.a)$$

$$C_w \frac{dT_w}{dt} = K_i(T_o - T_w) - K_o(T_w - T_i) \quad (3.1.b)$$

$$C_e \frac{dT_e}{dt} = K_e(T_o - T_e) - Q_{emb} \quad (3.1.c)$$

Where, T_o -Steady state temperature of outlet air, °C

T_w - Mean wall temperature of incubator, °C

T_i - Steady-state heat input, W

C_o - Thermal capacitance of air contained in the heating chamber, J/K

C_w - Lumped thermal capacitance of the structure (wall of the incubator), J/K

K_f - Convective conductance scribed to ventilation, W/K

K_i - Convective conductance between the enclosed air and structure node, W/K

K_o - Convective conductance between the structure node and the outside air, W/K

K_e - Thermal conductance of egg (W /K)

Q_{emb} - Embryonic heat production

Here the thermal conductance K_e of an egg incubator system comprises the internal conductance of egg incubator which associated with the heat flow between the inside of the egg and its surface. The external conductance of egg incubator system associated with the heat flow between the egg's surface and the boundary layer of air. In [12], the approximation of thermal conductance of egg incubator $K_e = (0.97v^{0.6})m^{0.53}$ was used in the egg incubator and it also depends on the speed of the ventilator. Where v - is speed (which was estimated as 1.0cm/s and assumed constant for this thesis study) and m -is egg mass (grams).

For the analysis of heat transfer between an egg and egg incubator system with initial condition, the following assumptions were made as follows:

1. The egg approximated spherical shape with geometric mean diameter, $D = 4$ cm.
2. Energy conduction in the egg was one-dimensional because symmetry about its Centre.
3. The temperature property of the egg was fixed.
4. The energy transfer coefficient was fixed and uniform over the entire surface.

The temperature trajectory of egg incubator taken in the center by setting temperature $T_{in}(t)$ initially and final temperature placed in the egg incubator at $T_{\infty} = 37.5^{\circ}\text{C}$ could be calculated. Temperature that found in center of the egg in the sphere was given as follows (3.2):

$$\theta = \frac{T_c(t) - T_\infty}{T_{in} - T_\infty} = A_1 e^{-\lambda^2 \tau} \quad (3.2)$$

Where θ is a dimensionless quantity of egg incubator that denotes change in temperature, $\tau = F_o$ was the Fourier number given by $F_o = \frac{\beta t}{D^2}$ with β being thermal diffusivity of water at 37.5 °C and D the characteristic diameter. The constants A_1 and λ_1 was the functions of the Biot number and are found in transient temperature charts. The Biot number, B_i is given by (3.3) as;

$$B_i = \frac{hD}{\alpha} \quad (3.3)$$

Where h was convective heat transfer coefficient over the egg's surface, D was diameter egg and k was thermal conductivity. The egg was approximated to a sphere (of diameter $D = 4$ cm) filled with water yield $\alpha = 0.6$ W/m²°C. The convective heat transfer coefficient h (in $\frac{W}{m^2°C}$) computed as (3.4)

$$h = 0.62 * 3.284 * (1.37 + \sqrt{100v}) \text{ W/m}^2\text{°C} \quad (3.4)$$

By using these values with the speed of air $v = 1$ m/s which gives $B_i = 1.073$ and the corresponding the values egg incubator system for A_1 and λ_1 were 1.5708 and 1.2732, respectively solved. From (3.4), states that the smaller size of egg and the faster the air (the higher the velocity, v), the more accurate the model egg incubator system. Then the egg centerline temperature $T_c(t)$ given by (3.2) was computed as follows by assuming for the egg initially $T_{in} = 27.5$ °C. The model of egg incubator system now confirm that the validity of the one term approximated solution for one dimensional transient conduction in the sphere could be calculated as follows:

$$\tau = -\frac{1}{\lambda_1^2} \frac{(T_c(t) - T_{air})}{A_1(T_{in} - T_{air})}$$

3.3 STATE-SPACE REPRESENTATION OF AN EGG INCUBATOR SYSTEM

State space model was commonly used for represent the linear time-invariant system. It also describe the system with the set of first order differential or difference equation using inputs, outputs, and state variables. The models also could be applied to nonlinear systems or systems with non-zero initial conditions. They besides be responsible for the suitable way to denote, analyze, and control multi-input/multi-output (MIMO) systems. From the egg incubator system the inputs, output and states from above (3.1), then it was summarized as follows in table 3.1.

Table3.1: State-space parameters of an egg incubator

System parameters	Designation
Inputs	$Q_i(t), T_i(t), Q_{emb}(t)$
Outputs	$T_o(t), T_e(t)$
States	$T_o(t), T_w(t), T_e(t)$

By rearranging the (3.1) and designating the input parameters $T_i(t)$, $Q_i(t)$ and $Q_{emb}(t)$ respectively as $u_1(t)$, $u_2(t)$ and $u_3(t)$ the following (3.5) obtained:

$$\dot{T}_0 = \frac{-(K_f+K_i+K_e)}{C_o} T_0(t) + \frac{K_i}{C_o} T_w(t) + \frac{K_e}{C_o} T_e(t) + \frac{1}{C_o} u_1(t) + \frac{K_f}{C_o} u_2(t) \quad (3.5.a)$$

$$\dot{T}_w = \frac{-(K_i+K_o)}{C_w} T_w(t) + \frac{K_i}{C_w} T_0(t) + \frac{K_o}{C_w} u_2(t) \quad (3.5.b)$$

$$\dot{T}_e = \frac{-K_e}{C_e} T_e(t) + \frac{K_e}{C_e} T_0(t) - \frac{1}{C_e} u_3(t) \quad (3.5.c)$$

By transforming (3.5) into standard state space matrix form yields the (3.6):

$$\begin{bmatrix} \dot{T}_0 \\ \dot{T}_w \\ \dot{T}_e \end{bmatrix} = \begin{bmatrix} \frac{-(K_f+K_i+K_e)}{C_o} & \frac{K_i}{C_o} & \frac{K_e}{C_o} \\ \frac{K_i}{C_w} & \frac{-(K_i+K_o)}{C_w} & 0 \\ \frac{K_e}{C_e} & 0 & \frac{-K_e}{C_e} \end{bmatrix} \begin{bmatrix} T_0(t) \\ T_w(t) \\ T_e(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{C_o} & \frac{K_f}{C_o} & 0 \\ 0 & \frac{K_o}{C_w} & 0 \\ 0 & 0 & -\frac{1}{C_e} \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} \quad (3.6)$$

Since the measured outputs was the air temperature $T_o(t)$ and egg shell temperature $T_e(t)$ and then the output equation could be written as:

$$y(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T_0(t) \\ T_w(t) \\ T_e(t) \end{bmatrix} \quad (3.7)$$

The (3.6) and (3.7) derived above was rearranged as the standard ABCD form as follows:

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

CHAPTER FOUR

4. CONTROLLER DESIGN

4.1. CONTROL THEORY OVERVIEW

Generally, the control theory was deals with the system behavior and control accent on principles, design and construction of the control system. The key goal of the controller system philosophy was consists the behavior of controlled plant, expected output to meet the criteria and system constraints. Temperature control was the important environmental parameter for egg incubator system for egg growth. Because the growth or a reaction culture may be influenced by varying fluctuations in temperature throughout the interior chamber of egg incubator system.

However, for the developing embryo temperature which experiences inside the egg that determines the development of the embryo. This must be considered the real incubation temperature egg incubator system. To achieve this goal optimal temperature controller for egg incubator designed. MPC have capability of checking plant's output, error computation and calculating the appropriate control signal.

The above steps with calculated of optimal temperature control action based on the control error was described the closed loop or feedback of MPC controller. Feedback controller of MPC takes corrective action as input system by calculating the difference between actual and desired output value. The second approach in this control philosophy was called open-loop controller of MPC which calculate its control signal as input into output system using present state and the system model. Here feedback MPC was used because the egg incubator system have interconnection of two or more dynamical system where interconnected together like system effect the other and their dynamic were interconnected.

4.2. MODEL PREDICTIVE CONTROL

The predictive control was advance control method which used to solve the complex control problems. It was the model-based the mathematical approach which used for the output values prediction explicitly a process or system model in order to obtain the control actions. Model predictive control was refer to class of control algorithms that calculated sequence of control moves based on an explicit prediction of output with in some future horizon. It was also the method to

obtaining the feedback controller from knowledge of open loop controller was to measure the present control process state and then calculate very rapidly for open-loop control.

The primary portion of this in the egg incubator was then used during short time instant after which update measurement of the task was calculated for this update measurement. Otherwise the method was then repeated. The only first value of resulting optimal temperature variable solution was given to the egg incubator system and the next solution is discard. The same mechanism was repeated in every sampling interval (time) and output prediction horizon was moved to next step. Since then, MPC of temperature control of egg incubator was the bridge for the complicated constrain multi-variable control in the agricultural industries for income generation for those farmers live in Rural and Urban areas of the Ethiopia.

It was type of control, at each sampling time start the current state of open loop optimal temperature control problem of egg incubator was calculated over the finite horizon. At the next time step, the calculation was repeated starting from updated state and over the shifted horizon, leading to the residing horizon policy of MPC to controlling temperature of egg incubator. Then the solution was relies on the linear dynamic model, respects stated constraints, and improves a quadratic performance index. Thus the provided that the egg incubator model was accurate, then the current and future moves of the MVs of an egg incubator were selected.

The deviation of the controlled variable (CV) of egg incubator system to the desired target (set point) was reduced by using objective function. At next of the time step $k + 1$, the measurement was taken, the horizon which was shifted forward by the one step. The optimization done again over the shifted horizon based on the updated prediction of the egg incubator system behavior. Therefore, this control strategy was also some time referred to as moving horizon control (receding horizon control).

The predictions were necessary to solve the optimization of temperature of egg incubator problem, which was obtained using the mathematical model of egg incubator system. The prediction of organized variable was executed using sampling interval with length H_p samples. H_p and H_u were referred to the prediction horizon and control horizon respectively. The difference between the prediction and control horizons was useful since the number of command variable in optimization

temperature control of egg incubator system increases with H_u , but was independent of H_p . Normally, $H_u < H_p$ in order to minimize the complication of optimization of egg incubator problem. While solution of best temperature of egg incubator system problem was obtained, then the first control variable value in optimal temperature of egg incubator trajectory $u(k/k)$ was given to the egg incubator system to control its temperature in the optimal level for safe operation.

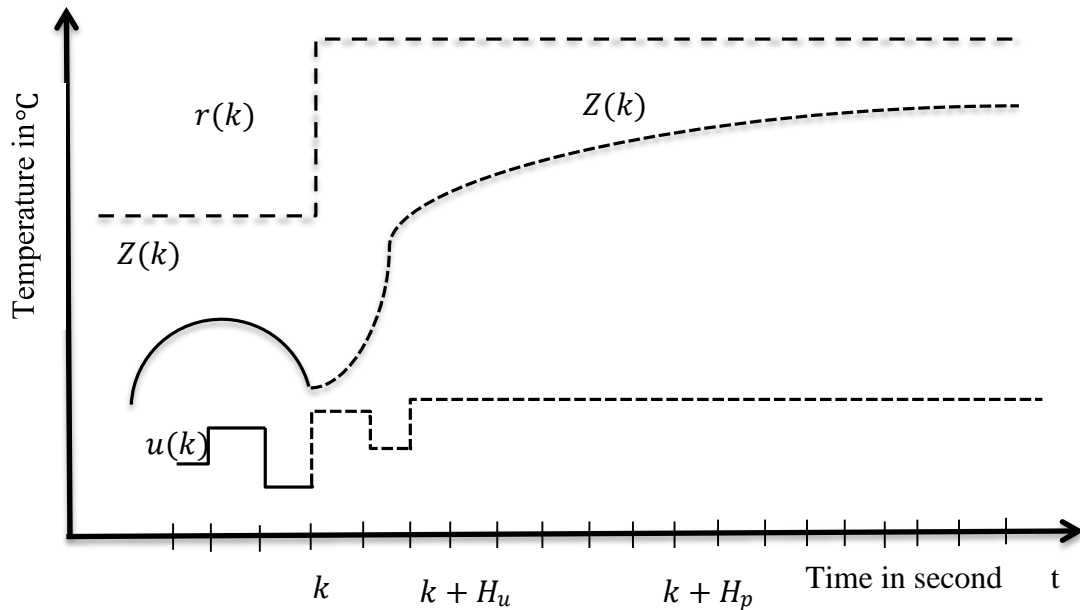


Figure 4.1. The elementary idea of model predictive control

Where $r(k)$ is the set point trajectory, $z(k)$ represents the controlled output and $u(k)$ the control signal or manipulated variable. Temperature control of egg incubator system using MPC was used to design the optimal temperature controller which keeps the stability and performance even the model inaccuracies. In this thesis the finite prediction horizon linear quadratic regulator algorithm was used to simplify computation.

4.3. MPC MODEL OF AN EGG INCUBATOR SYSTEM

Then the MPC model of an egg incubator system was developed as follows in (4.1):

$$X(k + 1) = AX(k) + Bu(k) \quad (4.1.a)$$

$$y(k) = C X(k) \quad (4.1.b)$$

$$z(k) = C_z X(k) + D_z u(k) \quad (4.1.c)$$

$$z_c(k) = C_c X(k) + D_c u(k) \quad (4.1.d)$$

The MPC controller must respect constraint on control variables as well as output, $Z_c(k) \in \mathbb{R}^{pc}$

- $\Delta u_{\min} \leq \Delta u(k) \leq \Delta u_{\max}$
- $Z_{\min} \leq Z_c(k) \leq Z_{\max}$,
- $\Delta u(k) = u(k) - u(k - 1)$ are the control gradient
- System weight, if the larger ratio $W_y W \Delta u$, then more destructive the controller.
- Control horizon: if the larger H_u , then solution was more optimal but controller to be difficult.
- Prediction horizon: if the smaller H_p , then the controller was quickly achieve the result.
- Limit: if the controller have slowly achieve the result when Δu_{\min} and Δu_{\max} were small.

Finally we always try to set H_u as small for tuning purpose, because if we setting the larger H_u makes the controller more complex.

4.4. MPC STRATEGY OF AN EGG INCUBATOR SYSTEM

The MPC strategy for optimal temperature of an egg incubator is represented as in Figure 4.2 below is summarized the following basic points:-

1. The future outputs temperature of egg incubator for a determined horizon (N), called the prediction horizon (H_u) was predicted at each instant t using the egg incubator model. All the predicted output rely on the known values which were past input and output and on the future control signals $u(t+k)$, $k=0, \dots, N-1$.
2. Optimization used to calculate future temperature control signals of egg incubator in order to keep the egg incubator system as close as possible to the reference trajectory $r(t+k)$. That was use the criterion that typically proceeds in the form of the quadratic function of the error between the expected output signal and the predicted reference trajectory. An explicit solution could be obtained if the criterion is quadratic, then in this thesis the linear model

of an egg incubator system was used to design the controller. Otherwise the iterative temperature optimization method has to be used for egg incubator.

3. The temperature control signal was sent to egg incubator system. For this strategy, the model was used to predict the future egg incubator system output temperature. Based on the past and current values proposed optimal temperature sent for future control actions. These actions was calculated by optimizer taking into account the cost function (where the future optimal temperature tracking error was considered) as well as the constraints.

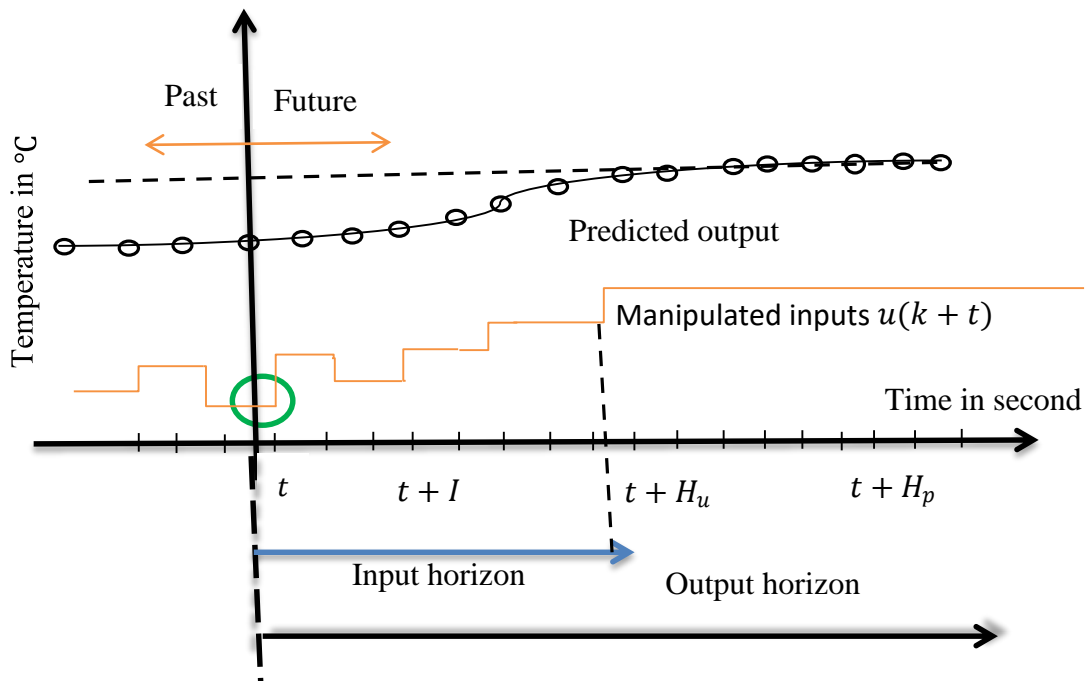


Figure 4.2 Receding Horizon strategies of an egg incubator system by using MPC

4.5. TUNING ALGORITHM OPTIMAL TEMPERATURE CONTROL OF SYSTEM

In continuous time MPC design tuning guideline, the parameters were p - pole location, H_u - control horizon, H_p -prediction horizon and the weighting matrix Q and R were also used MPC model of egg incubator system for future temperature control signal. The estimate values of weighting matrices like \hat{Q}_o and \hat{R}_o to simplify tune the controller to be settled.

4.5.1 PREDICTION HORIZON H_p

Aimed at stable plant, prediction horizon was advisable to be chosen nearly equal to the open loop egg incubator settling time, i.e. the time determined the when the response was reached 99% of its final value.

4.5.2 POLE LOCATION p

Pole location p was tuning constraint for closed-loop of egg incubator system response. If greater p result in larger variation in future egg incubator temperature control signal in the initial time, hence quick closed loop egg incubator system response speed. The effective modification method for p was to start around location of egg incubator system main pole and then speed up or less aggressive the feedback response by variation of speed value of pole to achieve the expected objective. The temperature performance limit was reached up or down when p no longer variation closed-loop temperature response increase.

4.5.3 CONTROL HORIZON H_u

If control horizon H_u increased, then the degree of freedom described control trajectory to be increased. The egg incubator temperature control signal be wont to to be quickly achieve the result when H_u increased. If $N=1$, the temperature control trajectory was constrained to first order response, which produce desirable feedback temperature control response for majority of the stable system. Here this thesis the designed system was second order ($N=2$) and $H_u =3$ was often chosen for tuning purpose, then temperature control system trajectory was constrained to have second order response, which produce desirable closed loop temperature of egg incubator system response for majority of stable.

4.6 OPTIMIZATION TEMPERATURE CONTROL PROBLEM

The term optimization of temperature control of an egg incubator system implies that the best value for some types of the performance criterion. Here, we first discuss possible objective functions, then possible egg incubator models that can be used for MPC. The objective function was summation of square of the predicted errors and the control moves or changes in control action from step to step. The quadratic objective function for the $H_p = 3$ and $H_u = 2$ can be written in (4.2)

$$J = (r_{k+1} - \hat{y}_{k+1})^2 + (r_{k+2} - \hat{y}_{k+2})^2 + (r_{k+3} - \hat{y}_{k+3})^2 + (w\Delta u(k))^2 + (w\Delta u(k+1))^2 \quad (4.2)$$

where \hat{y} -denote the model expected output, r - the set point, Δu was the change in the manipulated input from one sample to the next, w was the weight for deviations in operated input and the subscripts indicate the sample time (k was the current sample time).

If the value of $H_p = 1$ and $H_u = 1$ selected, then the performance index could be given as in (4.3):

$$J = \sum (r_{k+1} - \hat{y}_{k+1})^2 + \sum (w\Delta u(k))^2 \quad (4.3)$$

In this thesis the following objective used by selecting values of $H_p = 10$ and $H_u = 3$ for control tuning, then the quadratic function become given as:

$$J = |r_{k+1} - \hat{y}_{k+1}| + |r_{k+2} - \hat{y}_{k+2}| + \dots + |r_{k+10} - \hat{y}_{k+10}| + w|\Delta u_k| + \dots + w|\Delta u_{k+3}| \quad (4.4)$$

This has the following general form for H_p and H_u was given as:

$$J = \sum |(r_{k+1} - \hat{y}_{k+1})| + w\sum |\Delta U_{k+1}| \quad (4.5)$$

The optimization of temperature control calculated as minimization of performance function was obtained by correcting the H_u control horizon which subject to the plant model equation and constraint on the input and output. The absolute value of the performance index used in little procedure become linear quadratic regulator (LQR).

$$\min_U J(U,t) = x'(t+N|t)Px(t+N|t) + \sum_{k=0}^{N-1} \{x'(t+k|t)Qx(t+k|t) + u'(t+k)Ru(t+k)\} \quad (4.6)$$

Infinite prediction horizon of LQR procedure with the powerful temperature control stabilizing used in this thesis. The properties of an egg incubator system was stabilized and detected as long as the performance index weighting matrices Q and R should be positive definite. Then the objectives function of optimal temperature control of an egg incubator system given as follows:

$$J_N(x_o, u^N) = \min_{u^N} \left[\sum_{k=0}^{N-1} (x_k^T Q x_k + u_k^T R u_k) + x_N^T P_o x_N \right] \quad (4.7)$$

Where Q and R were weighting matrices and P_o was the terminal weight which pragmatically taken to be equal to the nominal state weight, i.e. $P_o = Q, R = R' > 0, Q = Q' > 0$. They are positive definite and finally Reccatti equation must be calculated as follows:

$$P = A'PA - A'PB(B'PB + R)^{-1}B'PA + Q \quad (4.8)$$

If the MPC was unconstrained then it look like linear quadratic regulator (LQR) and the controller works as the feedback controller K. The closed loop matrix A_c of optimal temperature control of an egg incubator system was computed as follows:

$$A_c = A - BR^{-1} B^T P \quad (4.9)$$

The optimal temperature vector $u(t)$ of an egg incubator system could be switches or removes if there was non-minimum phase (delay) part. As the closed-loop system matrix A_c computed above (4.10) does not hold any time delay for instant, the one could easily use the mechanism of direct pole placement to obtain the desired closed loop time specification measured. Then the observer equation was computed as follows:

$$\dot{X}(t) = A_c X(t) \quad (4.10)$$

The matrix A_c could be determined by setting the characteristic equation of the closed loop of optimal temperature egg incubator system, then the desired closed loop equation computed as:

$$\Delta s = |sI - A_c| \quad (4.11)$$

Then the value of optimal feedback controller K was obtained from the MATLAB™ command and the temperature control signal of egg incubator computed as follows:

$$\begin{aligned} [K, P] &= \text{lqr}(A, B, Q, R) \\ u(t) &= -R^{-1}BK \end{aligned} \quad (4.12)$$

Where K is state feedback (optimal temperature controller) gain matrix and P is the Reccatti matrix. The observer equation that was needed for implementing of the continuous time MPC of egg incubator system was given by:

$$\dot{\hat{X}}(t) = A\hat{X}(t) + B\dot{u}(t) + K_{ob}(y(t) - C\hat{X}(t)) \quad (4.13)$$

Where $\hat{X}(t)$ -the estimate of $X(t)$ and K_{ob} - the observer gain and $\dot{u}(t)$ was calculated from the optimal temperature solution of the MPC policy either using the analytical solution (quadratic programming) mechanism. If the developed egg incubator system model (A, B, C) was totally observable, then K_{ob} was chosen as the error $\bar{X}(t) = X(t) - \hat{X}(t)$ which decay exponentially at desired rate.

COMPUTATION OF STATE WEIGHTING AND RICCATI COEFFICIENT MATRICES

In case of second order plant the matrices Q, R and P were generally given as:

$$Q = \begin{bmatrix} q_1 & 0 & 0 \\ 0 & q_2 & 0 \\ 0 & 0 & q_3 \end{bmatrix}, P = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} \text{ and } R=[r]$$

In use design of LQR by changing Q and keeping R constant, then the state-space formulation Q and P matrix of the system become derived as follows: -

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \text{ and } y(t) = Cx(t) + Du(t) \\ |sI - A_c| &= s^3 + (a + \eta p_{33})s^2 + (b + \eta p_{23})s + \eta p_{13} \\ &= s^3 + (2 + m)\epsilon_{cl}\omega_{cl}s^2 + (\omega_{cl}^2 + 2m\omega_{cl}^2\epsilon_{cl}^2)s + \epsilon_{cl}\omega_{cl}^3 \end{aligned}$$

Therefor characteristic equation of derived mathematical model was given as:

$$|sI - A_c| = s^3 + 10s^2 + 64s + 168$$

By comparing

$$p_{13} = \frac{\epsilon_{cl}\omega_{cl}^3}{\eta}, \quad p_{23} = \frac{\omega_{cl}^2 + 2m\omega_{cl}^2\epsilon_{cl}^2 - b}{\eta}, \quad p_{33} = \frac{(2+m)\epsilon_{cl}\omega_{cl} - a}{\eta}$$

The continuing extract matrix coefficient computation as follows:

$$\begin{aligned} p_{11} &= \frac{m\epsilon_{cl}\omega_{cl}^5(1+2m\epsilon_{cl}^2)}{\eta}, & p_{12} &= \frac{(2+m)m\epsilon_{cl}^2\omega_{cl}^4}{\eta}, \\ p_{22} &= \frac{2\omega_{cl}^3(\epsilon_{cl} + 2m\epsilon_{cl}^3 + m^2\epsilon_{cl}^3) - ab}{\eta}, & q_1 &= \frac{m^2\epsilon_{cl}^3\omega_{cl}^6}{\eta} \\ q_2 &= \frac{\omega_{cl}^4(1+4m^2\epsilon_{cl}^4 - 2m^2\epsilon_{cl}^2) - b^2}{\eta}, & q_3 &= \frac{\omega_{cl}^2(4\epsilon_{cl}^2 + m^2\epsilon_{cl}^2 - 2) + 2b - a^2}{\eta} \end{aligned}$$

Evaluation of exponential solution become computed as:

$$\begin{aligned} e^{A(L-t)} &= e^{-1}[(sI - A)^{-1}] \\ A_c &= (A - BR^{-1}B^TP), \quad u(t) = -R^{-1}B^TPe^{A_cL} \end{aligned}$$

4.7 MPC-CONTROLLER DESIGN

4.7.1. PREDICTIVE MODEL OF AN EGG INCUBATOR

There are three universal methods used in predictive control system design. The first method of model predictive control design was finite impulse response (FIR) model and step response model were favored. The second mechanism of model predictive control design was transfer function model which give more exhibited description of process dynamic and were applicable for both stable and unstable system. The third mechanism of model predictive control design was state-space design method. In this thesis, the state-space model methods was used for simplicity of design to classical linear quadratic regulator. Predictive control model was designed with initial condition response and control response as follows:

$$Y = \Phi x(k_i) + F \Delta u \quad (4.14)$$

Where $Y = \begin{bmatrix} y(t+1) \\ \vdots \\ y(t+N) \end{bmatrix}$ - is predicted output, $u = \begin{bmatrix} y(t+1) \\ \vdots \\ y(t+N) \end{bmatrix}$ - is future control input,

$x = x(t)$ - is current state and $u = u(t)$ is computed previous step

The predictive egg incubator system model matrices can be competed as follows:

$$F = \begin{bmatrix} CA \\ \vdots \\ CA^{H_p} \end{bmatrix} = \begin{bmatrix} h(2) \\ h(3) \\ \vdots \\ h(H_p + 1) \end{bmatrix} \quad (4.15)$$

$$\Phi = \begin{bmatrix} 0 & 0 & \dots & 0 \\ CB & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{H_p-2}B & CA^{H_p-3}B & \dots & CA^{H_p-H_u}B \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dots & 0 \\ h(1) & h(1) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ h(H_p) & h(H_p - 1) & \dots & h(1) \end{bmatrix} \quad (4.16)$$

By assume that the control signal $u(t)$ applied to the egg incubator, control horizon is 3, prediction horizon is 10 and state $x(t)$ was sampled at same instant t , then entire sampling interval was available for predictive model could be calculated as follows:

$$\Phi = \begin{bmatrix} 0 & 0 & 0 \\ CB & 0 & 0 \\ CAB & CB & 0 \\ CA^2B & CAB & CB \\ CA^3B & CA^2B & CAB \\ CA^4B & CA^3B & CA^2B \\ CA^5B & CA^4B & CA^3B \\ CA^6B & CA^5B & CA^4B \\ CA^7B & CA^6B & CA^5B \\ CA^8B & CA^7B & CA^6B \end{bmatrix}, \quad F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ CA^4 \\ CA^5 \\ CA^6 \\ CA^7 \\ CA^8 \\ CA^9 \\ CA^{10} \end{bmatrix}$$

The incremental optimal temperature control within one optimization window was given by:

$$\Delta u = (\Phi^T \Phi + \overline{R}_s)^{-1} (\Phi^T \overline{R}_s r(k_i) - \Phi^T F x(k_i)) \quad (4.17)$$

Where matrix $\Phi^T \Phi$ has dimension $mH_u \times mH_u$ and $\Phi^T F$ has dimension $mH_u \times n$, and $\Phi^T \overline{R}_s$ equals the last q column of $\Phi^T F$. The weight matrix \overline{R}_s was block matrix with m blocks and its dimension equal to dimension of $\Phi^T \Phi$. Then the set point signal of egg incubator as q set point signal to multiple output system was given as: -

$$r(k_i) = (r_1(k_1) \ r_2(k_1) \ r_3(k_3))^T$$

By put on the receding horizon control standard, the first m elements in Δu are taken to form the gradient of optimal temperature control signal of an egg incubator and computed as: -

$$\Delta u = \overbrace{[I_m \ 0_m \ \dots \ 0_m]}^{N_c} m (\Phi^T \Phi + \overline{R}_s)^{-1} (\Phi^T \overline{R}_s r(k_i) - \Phi^T F x(k_i)) \quad (4.18)$$

$$\Delta u = K_y r(k_i) - K_{mpc} x(k_i)$$

$$\text{Where } K_y = [1 \ 0 \ 0] (\Phi^T \Phi + \overline{R}_s) (\Phi^T [1 \ 1 \ \dots \ 1]^T)$$

$$K_{mpc} = [1 \ 0 \ 0] (\Phi^T \Phi + \overline{R}_s) (\Phi^T F)$$

The optimal function for this thesis become:

$$J_N (x_o, u^N) = \min_{u^N} [\sum_{k=0}^{N-1} (x_k^T Q x_k + u_k^T R u_k) + x_N^T P_o x_N] \quad (4.19)$$

Finally, the design of optimal temperature controller for egg incubator system using MPC controller was realized for implementation as follows in block diagram form.

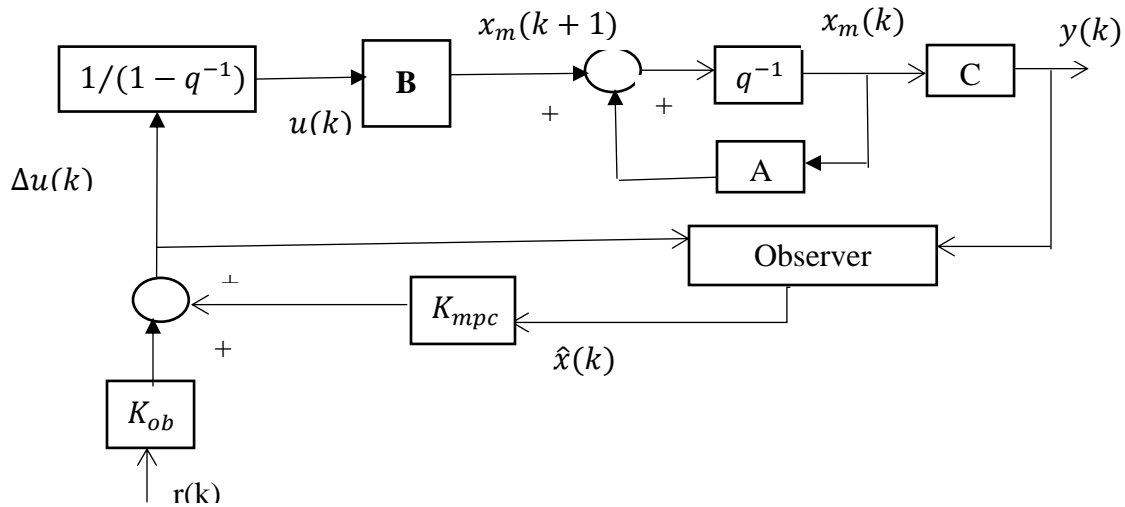


Figure 4.4 Block diagram of the DMPC (discrete MPC controller)

The overall transfer function of optimal temperature controller for egg incubator system using discrete MPC computed as follows:

$$\det[\lambda I - \begin{bmatrix} A - K_{ob}C & 0_{n \times n} \\ -BK_{mpc} & A - BK_{mpc} \end{bmatrix}] = 0 \quad (4.20)$$

Then the (4.20) was rearranged as follows:

$$\det(\lambda I - (A - K_{ob}C)) \det(\lambda I - (A - BK_{mpc})) = 0 \quad (4.21)$$

From the MAT LAB™ command could produce the observer gain vector K_{ob} . If the system unconstrained the controller look likes as MPC=linear quadratic regulator (LQR) and the controller works as the optimal state feedback temperature controller K. Then the Reccatti matrix and closed-loop matrix of the egg incubator system given as follows:-

$$P = A'PA - A'PB(B'PB + R)^{-1}B'PA + Q$$

$$Ac = A - BR^{-1} B^T P$$

$$\text{Closed loop pole} = [0.02 \ 0.0305 \ 0.021];$$

$$K_{ob} = \text{place}(A', C', \text{Pole});$$

$$[K_{mpc}, P] = \text{lqr}(A, B, Q, R)$$

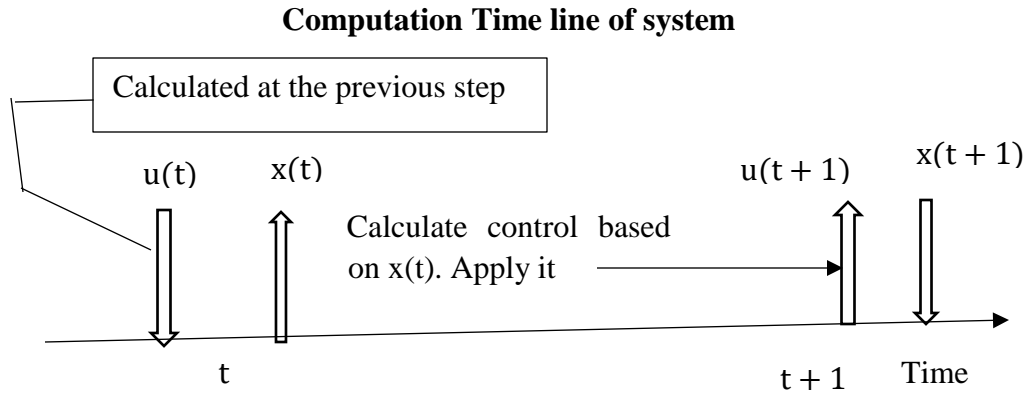


Figure 4.5 computation time for system

4.7.2. MPC OPTIMIZATION PROBLEM SETUP

The MPC optimization temperature control of an egg incubator problem was given as:

$$J = (Y^T Y + r(U^T D^T D U)) \quad (4.22)$$

subject to: $|U| \leq u_0$

$$D = \begin{bmatrix} 1 & -1 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix}$$

Where D is difference matrix and in this thesis we use the the diamention of difference matrix D become:

$$D = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The QP problem solution of optimal temperature control of an egg incubator system given as follows:

$$x(t) \rightarrow [\text{MPC Problem, QPsolver}] \rightarrow u \rightarrow u(t+1) = u(1) \quad (4.23)$$

Then standard QP codes for the optimal temperature control of an egg incubator system can be used in MATLAB™ Simulink for simulation. In order to get the optimal control signal $u(t)$ need to be calculated from $e^{A_c t}$ by substituting $u^m(t)$ and observer equation given as follows:

$$\dot{X}(t) = A_c x(t)$$

By using the matrix A_c the setting characteristic equation of the closed loop system determined as follows:

$$\Delta s = |sI - A_c|$$

4.8 MAIN PROS AND CONS OF MODEL PREDICTIVE CONTROL

MAIN PROS OF MODEL PREDICTIVE CONTROL WERE: -

- It could accept the nonlinear or switching or multiple input-multiple output dynamic with time delays.
- It could enforce constraint on input and output of plant.
- Its objective was optimized.
- Its design approaches methodical.
- MPC controller design was easy to fix.
- It accept the MATLABTM tool exist to help the design model and code generation.

MAIN CONS OF MODEL PREDICTIVE CONTROL WERE: -

- It was needs the simplified prediction model as all model-based mechanisms.
- It want non-minimum phase state estimate (observers).
- Its calculation problem more several than classical (linear) mechanisms.
- It was somewhat improved by the explicit reformulation and the calibration of want extra knowledge (multiple modification knob).
- MPC was continuously circulating in the industry.

4.9. PID CONTROLLER DESIGN

The PID controllers could be used to improve both the egg incubator system transient response and steady state errors. The PID controller was used to improve dynamic response as well as to reduce or eliminate the steady state error. If increasing controller gain, then the rise time and the steady state error were reduce. Derivative action was improve the transient response plant by reducing the overshoot and settling time. The diagram of closed-loop plant with PID controller for system was shown in Fig.4.6 below.

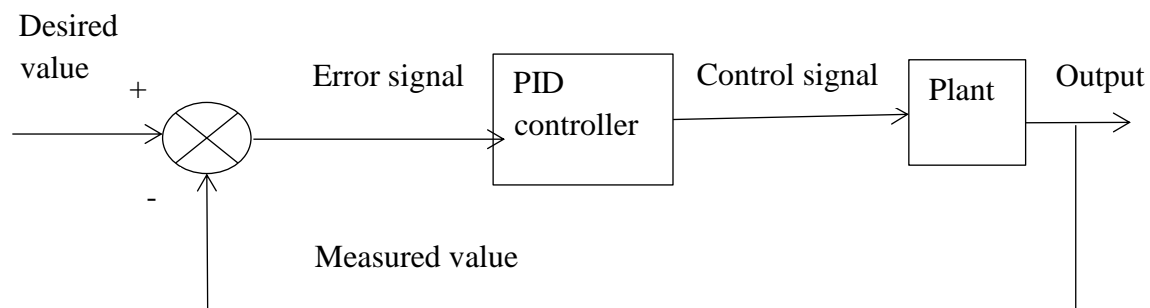


Figure 4.6 PID controller of closed-loop system

Then the state variables were listed as follows:

$$x(t) = [x_1 \ x_2 \ x_3]^T$$

Where, $x_1(t) = \int e(t) dt$, $x_2(t) = e(t)$ and $x_3(t) = \frac{de}{dt}$

If $e(t)$ was error, then it was calculated as: -

$$e(t) = r(t) - y(t)$$

Therefore, the command signal $u(t)$ was computed given as:

$$u(t) = K_p x_1(t) + K_I x_2(t) + K_D x_3(t)$$

With this situation, the second order transfer function including the time delay could be computed as:

$$C(s) = K_p + \frac{K_I}{s} + K_D s$$

If the third order transfer function derived from mathematical model of egg incubator system could be given as:

$$G(s) = \frac{y(s)}{u(s)} = \frac{ds + e}{s^3 + s^2 + as + b} = \frac{-e(s)}{u(s)}$$

Generally, by use the following MATLAB™ commands simulate using PID controller.

```
Gp = tf(num, den) % Plant transfer function
Gc = tf(kp((num,den)) % PI compensator
GPC = series(Gp, Gc) % Open loop transfer function
TF = feedback(GpGc, 1) % closed loop transfer function
ltiview('step', T) % obtains the step response
```

Effect of coefficients in controlling the system

Table 4.1 characteristics of closed loop parameters

Parameter	Speed of response	Stability	Accuracy
Increasing K_p	Increases	Deteriorate	Improves
Increasing K_I	Decreases	Deteriorate	Improves
Increasing K_D	Increases	Improves	No impact

CHAPTER 5

5. RESULT AND DISCUSSION

5.1 STABILITY OF THE EGG INCUBATOR

For a control system to be acceptable, the design must be internally stable for every model of egg incubator system in the set. The optimal temperature control of egg incubator system was stable if for all initial condition then bounded signal was injected at any place in the system and states remain bounded for all future time system should be stable. In this thesis the feedback system was used to check the stability of the developed model. All interconnected systems might be unavoidably subject to some nonzero initial condition and some error.

To check the stability of the egg incubator system in this thesis, first compute the Eigen value of matrix A that computed from mathematical model of an egg incubator. From the MATLAB™ command `eig(A)` the returned the vector of eigenvalues becomes:

$$\text{eig}(A) = [-2.8771 \pm 5.5938i, -4.2458 + 0.0000i]^T$$

The Eigen values of the egg incubator system was located at the left-hand side plane. This was shows that the egg incubator system was stable and the egg incubator system states were available for the feedback. Hence, the estimation of egg incubator system state from the given output information y and input u were often necessary to realize some specific design objectives. Suppose system was stable, then P and Q satisfied the following Lyapunov equations:

$$AP + PA^* + BB^* = 0$$

$$A^*Q + QA + C^*C = 0$$

Where the value of $P \geq 0$, $Q \geq 0$. Furthermore, the pair $(A; B)$ was controllable if $P > 0$, and $(C; A)$ was observable if $Q > 0$. Suppose the state an observer was dynamical system with input $(u; y)$ and output (say \hat{x}), that asymptotically estimates the state x , that was, $\hat{x}(t) \rightarrow x(t) \rightarrow 0$ as $t \rightarrow \infty$ for all initial states and for every input. From the Reccatti matrix value of P matrix was computed by using LQR method by using the MATLAB™ command as:

$$[k,P] = \text{lqr}(A,B,Q,R)$$

$$P = [4.7218 \quad 0.3532 \quad -0.1834; 0.3532 \quad 0.2258 \quad -0.0425; -0.1834 \quad -0.0425 \quad 0.1115]$$

Here in egg incubator system both P was Reccatti matrix and Q matrix are positive definite, this was shows that the egg incubator system was stable.

5.2 STEP RESPONSES EGG INCUBATOR WITH OUT CONTROLLER

The Simulink state variable model shown in Figure 5.2.1 was used to analyze system under different input conditions. The model was constructed from the parameters of state space matrices that determined from (3.6) and (3.7). The parameters were computed from physical data of egg incubator used control optimal temperature by using MPC. First we check the step response of an egg incubator system for inlet ambient air temperature $T_i = 38^\circ\text{C}$, supply heat $Q_i = 1\text{kJ}$ and embryonic heat $Q_{\text{emb}} = 0.25\text{J}$ was shown in Figure 5.2.2. It could be seen that in the case with zero input, both output values (incubator air temperature and egg shell (skin) temperature) were zero. Therefore, in this case the delay time was very high, to improve this by using the optimal temperature controller (MPC controller).

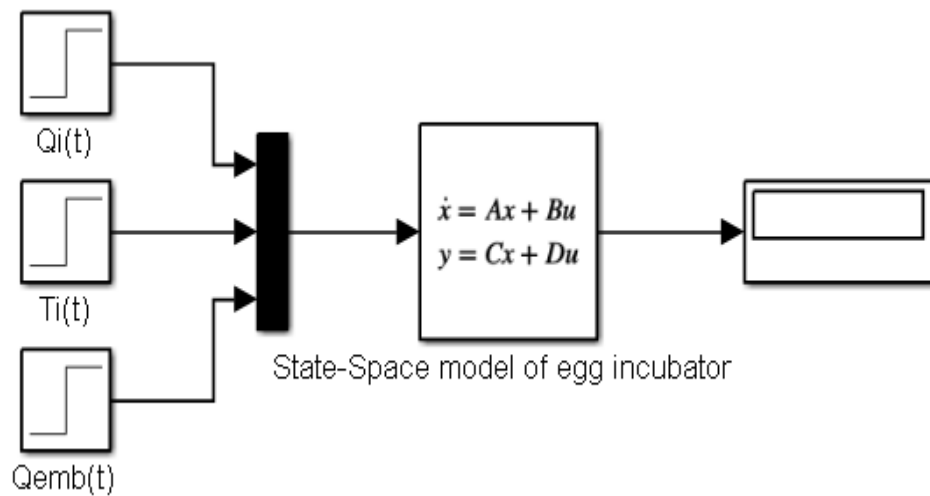


Figure 5.2.1 block diagram of Simulink state variable of egg incubator

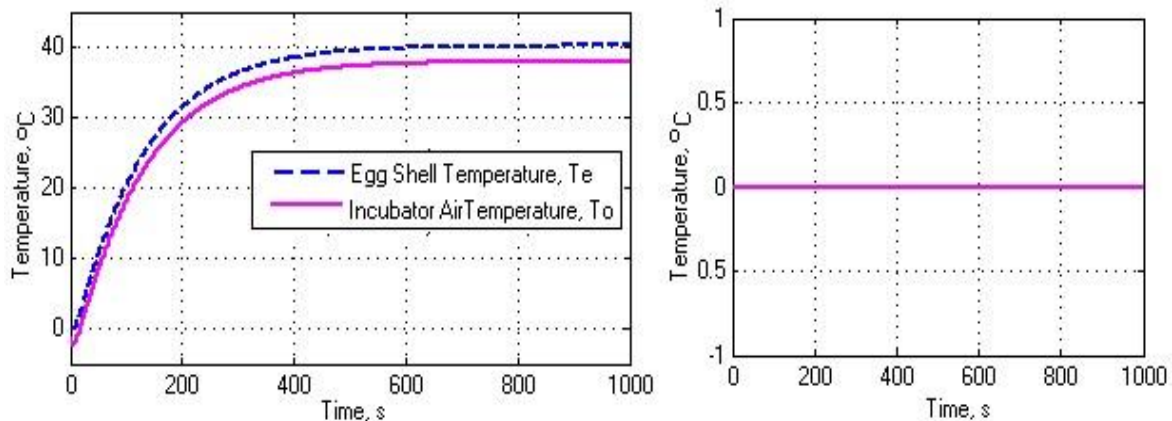


Figure 5.2.2 Step response of the egg incubator with (a) forced input and (b) zero input

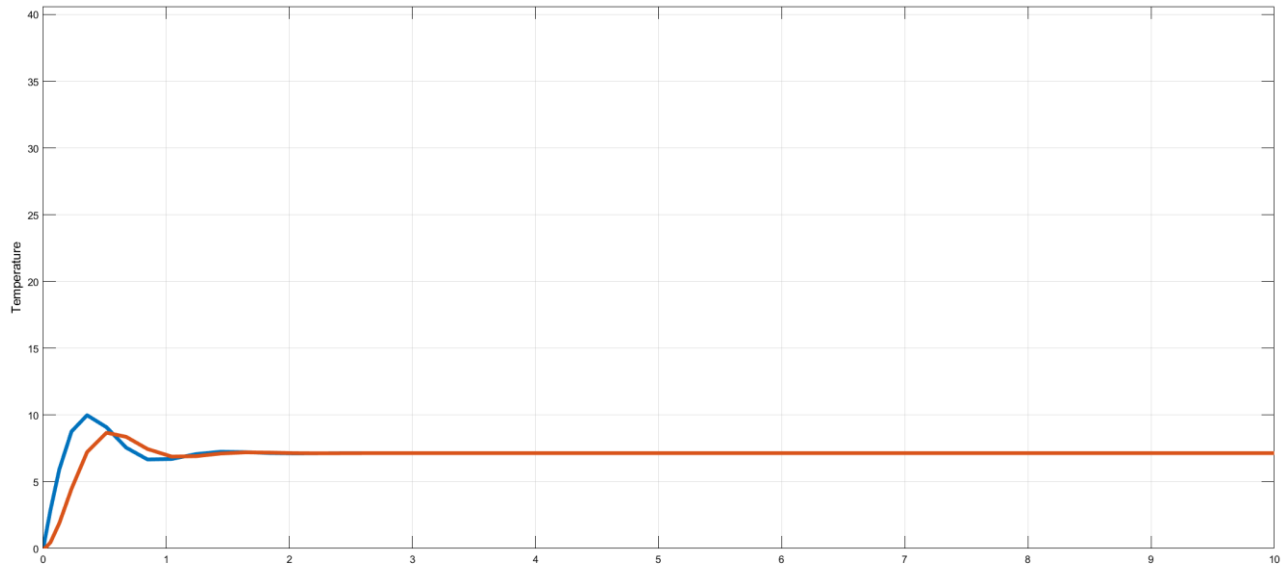


Figure 5.2.2 Step response of the egg incubator with zero input in ambient temperature

5.3. TEMPERATURE RESPONSE WITH INITIAL SET POINT OF SYSTEM

Step response with initial condition by using the code given in Appendix D as shown in figure 5.3

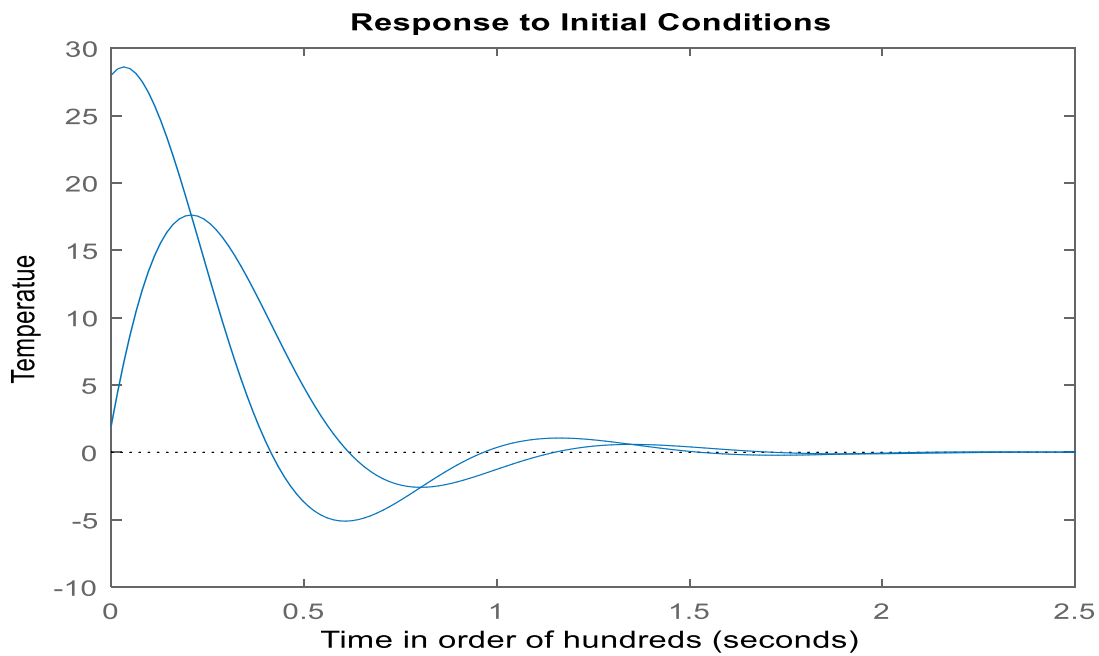


Figure 5.3 Step response of incubator system with initial condition

5.4. EGG CENTERLINE TEMPERATURE RESPONSE OF SYSTEM

By using (3.2), then the egg centerline temperature $T_C(t)$ response by assuming for the egg initially temperature was settled at ambient temperature $T_{in} = 25^\circ\text{C}$ and $T_\infty = 38^\circ\text{C}$ was shown in figure 5.3 as below.

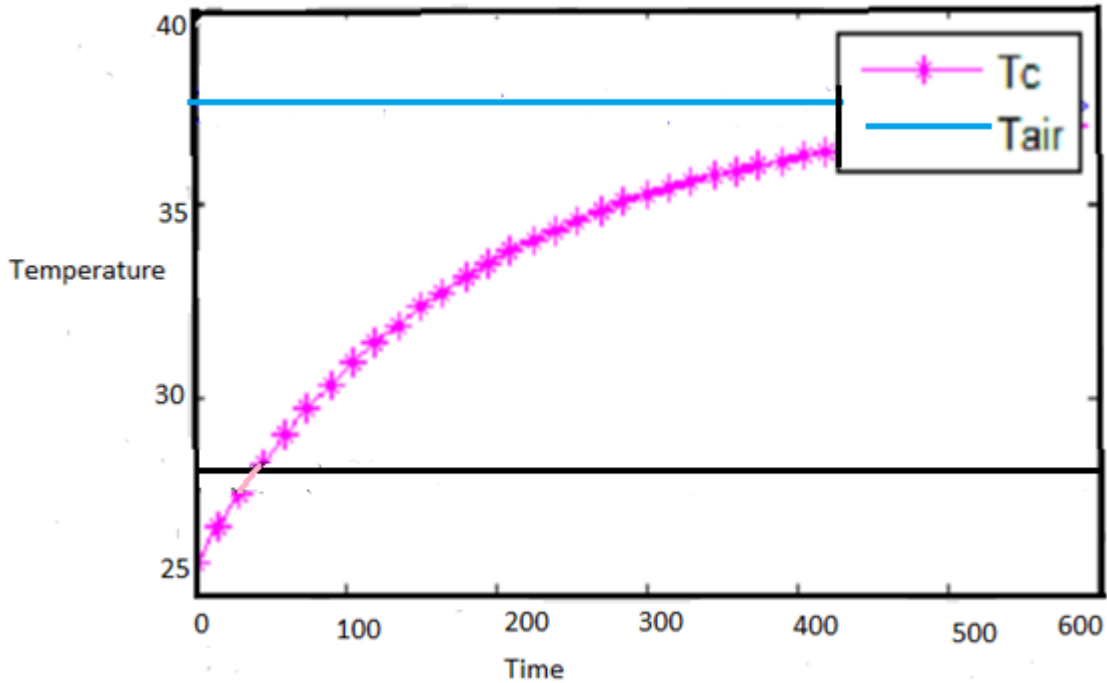


Figure 5.4 Response of egg center temperature with initial temperature

5.5. RESPONSE OF THE SYSTEM BY USING MPC MIMO

Therefore, in the above case the delay time was very high, to improve this case by using the optimal temperature controller (MPC controller). By using the MATLABTM Code for MPC designer were given as appendix A, the simulation results was shown in figure 5.5.

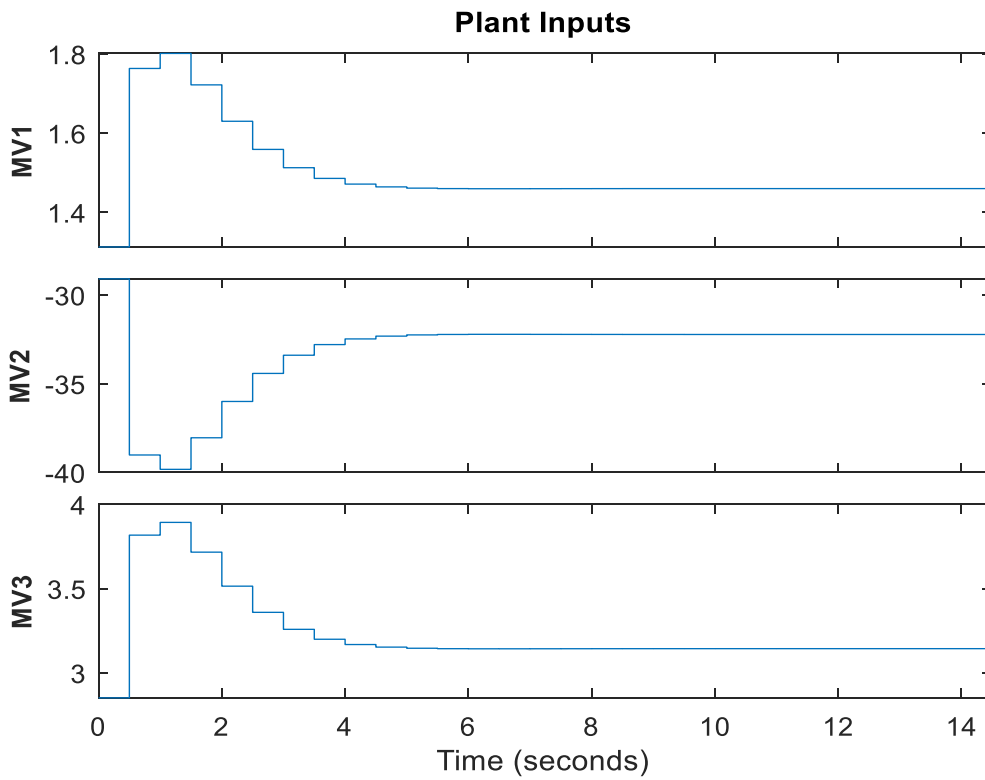


Figure 5.5.1: The controller sequence of the system of MPC

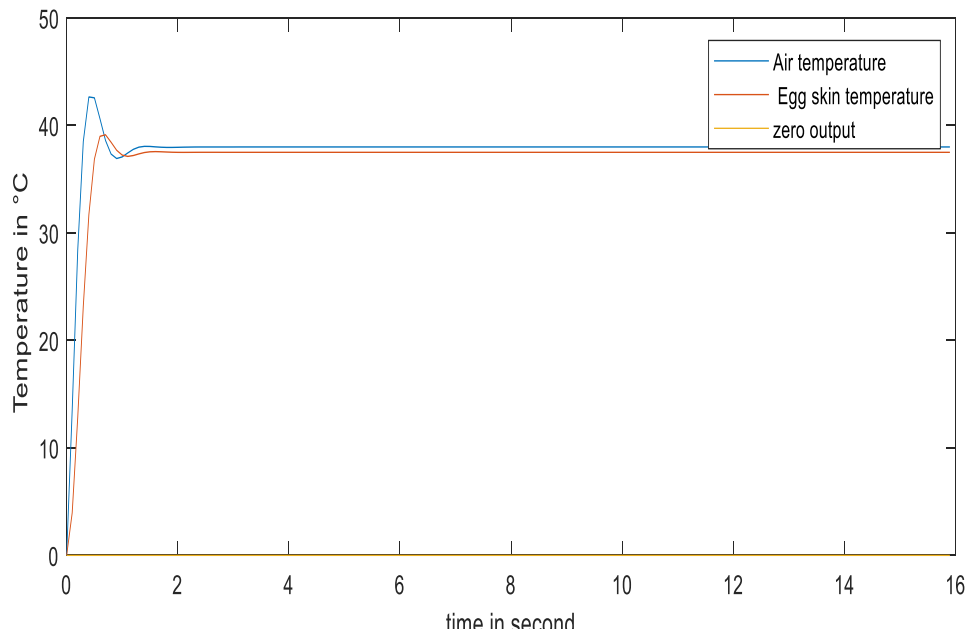


Figure 5.5.2: The output of the system without constraints

The figure 5.5.2 above shows that internal egg temperature were experienced by embryo more influential and converged on embryonic development and hatchability than air temperature with small settling time. The control specifications like settling time was improved in simulation by using MPC the average close to 37.1°C, but deviations of over 0.4°C could be founded depending on embryonic age. If the constraints used for the temperature control of an egg incubator system by using MPC were given below. The response of the optimal temperature control of an egg incubator system indicated in figure 5.5.3. The average temperature was close to 37°C depending on embryonic age with very small overshoot. The following constraints are used in in this thesis.

- 0.03 <= MV1 <= 2, -0.1 <= MV1/rate <= 4, MO1 is unconstrained
- 0.03 <= MV2 <= 2, -0.1 <= MV2/rate <= 4, MO2 is unconstrained
- 0.05 <= MV3 <= 2, 0 <= MV3/rate <= 0.5, MO3 is unconstrained

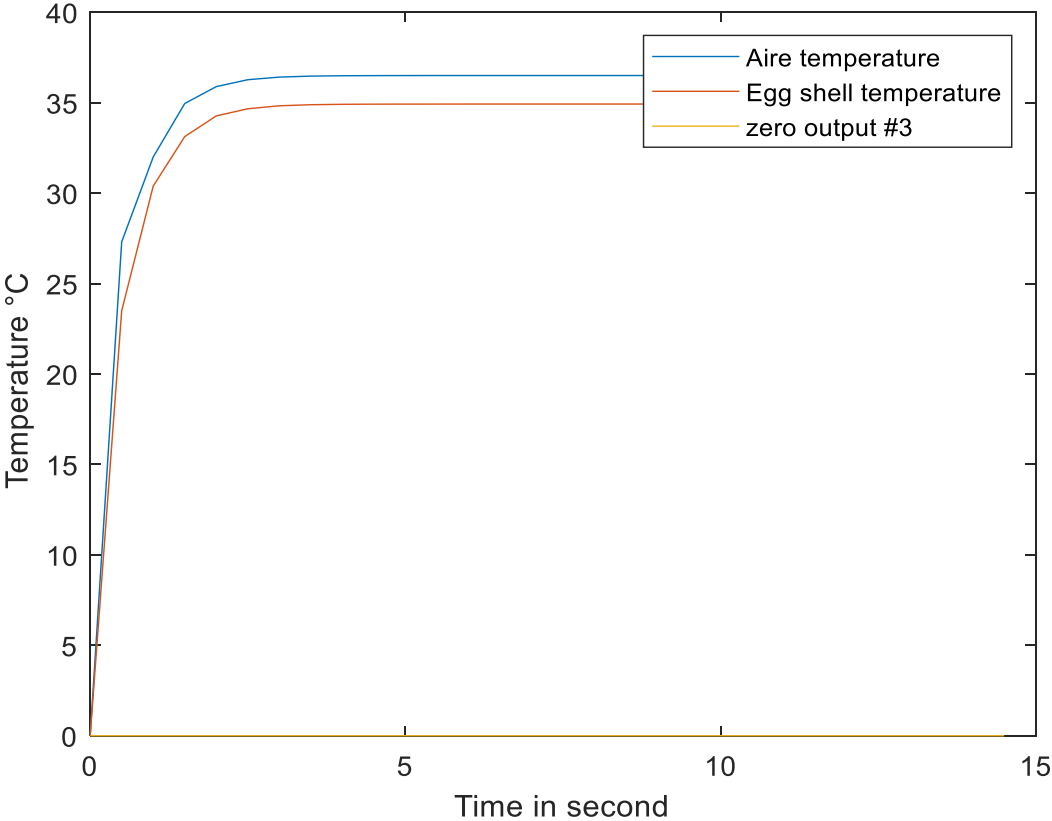


Figure 5.5.3: The output of the system with constraints

5.6 OPTIMAL CONTROL OR LQR OF AN EGG INCUBATOR SYSTEM

Now the value of decision (command) signal $u(t)$ computed by using value of K from MATLAB™ command.

$$[K, P] = \text{lqr}(A, B, Q, R)$$

Then value of control signal computed as:

$$u(t) = -R^{-1}BKx(t)$$

$$u = [-2.0381 \quad -0.0149 \quad 0.0477; -0.0004 \quad -0.0000 \quad 0.0000; 0.0000 \quad 0.0000 \quad -0.0000]$$

If we changing the value of control weighting matrix R as the $R = [1 \ 0 \ 0; 0 \ 37.5 \ 0; 0 \ 0 \ 0.5]$. Then the LQR controller and control signal u becomes:

$$K = [8.7216 \quad 0.5322 \quad -1.5621; -0.4793 \quad -0.0385 \quad 0.0918; 3.1242 \quad 0.6341 \quad -1.9227]$$

$$P = [4.3608 \quad 0.2661 \quad -0.7811; 0.2661 \quad 0.1906 \quad -0.1585; -0.7811 \quad -0.1585 \quad 0.4807]$$

The updated control signal become:

$$u(t) = -R^{-1}BKx(t)$$

$$u(t) = [-19.3605 \quad -1.2186 \quad 3.4913; -0.0256 \quad -0.0021 \quad 0.0049; 12.4970 \quad 2.5362 \quad -7.6910]$$

Finally the output response system becomes better to achieve all the control specifications.

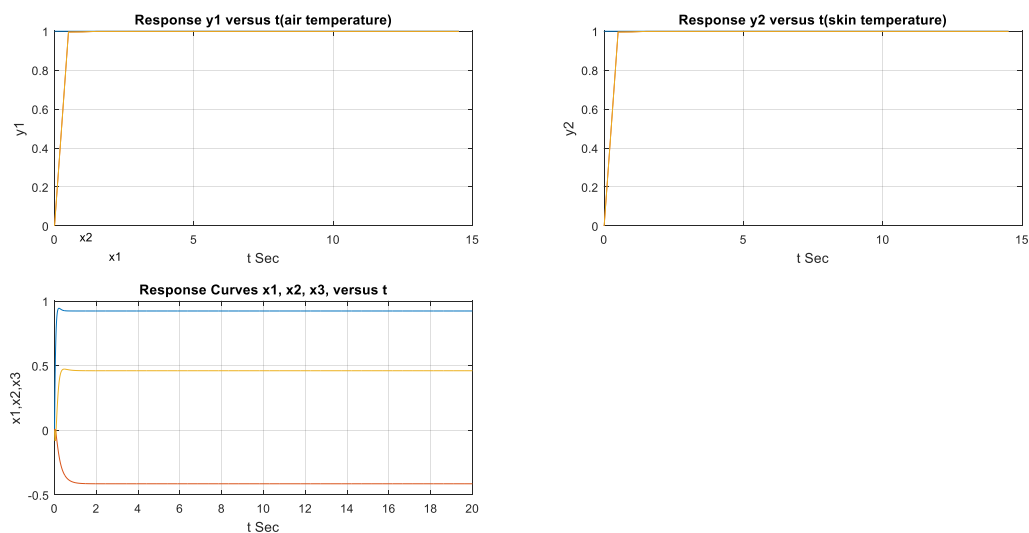


Figure 5.6 Response of system by using LQR

5.7. SENSITIVITY ANALYSIS OF THE SYSTEM

The sensitivity of control system to parameter variations was very important.

Previous sensitivity analysis

Output weights: $dJ/dW_y = [-10347.6, -166306]$

Output weights: $dJ/dW_y = [0,$ Input weights: $dJ/dW_u = [0, 157087, 2200.72]$ Input-rate weights: $dJ/dW_{du} = [10860.5, 358034, -5991]$

Updated Sensitivity analysis

Output weights: $dJ/dW_y = [598.545, -33888.6]$

Output weights: $dJ/dW_y = [0,$ Input weights: $dJ/dW_u = [0, 62437.1, 472.869]$

Input-rate weights: $dJ/dW_{du} = [252.773, 7901.44, -1194.01]$

Previous cumulated objective function $J_1 = 1.64536e+08$

New cumulated objective function $J_2 = 8.61984e+10$

The user defined cumulated objective function $J_3 = 8.61984e+10$ (similar with J_1).

Table 5.1 The sensitivity analysis of the controller

Constraint	Assumed Violation	Impact Factor	Sensitivity Ratio
Lower limit: T_out(2)	2	25	6.25e+04
Upper limit: T_out(2)	2	25	6.25e+04
Lower limit: T_out(3)	0.4	1	2500
Upper limit: T_out(3)	0.4	1	2500
Lower limit: T_out(1)	0.15	0.1406	351.6
Upper limit: T_out(1)	0.15	0.1406	351.6

If sensitivity fraction greater than $1e+08$, then the system might degrade QP solution accurateness.

Finally, the sensitivity ratio of the optimal temperature control using MPC of an egg incubator system was acceptable. This was shows that minimizations of cost function behaves its sensitivity and ISE converged to desired value quickly.

5.8. DESIGN REVIEW OF MODEL PREDICTIVE CONTROLLER (MPCOBJ)

Table 5.2 Summary of performance tasks were argued as follows

Performed tasks	Status
MPC object creation	Pass
QP hessian matrix validity	Pass
Controller internal stability	Pass
Closed-loop nominal stability	Pass
Closed-loop steady state gain	Pass
Other rigid constraint	Pass
Soft constraint	Pass

MPC object creation

Test for simulation whether in our objective criteria of the egg incubator was generated for the valid MPC to control the optimal temperature of the egg incubator using MATLAB™ software. Then the MPC object was ok then the following tasks could be proceeded. Otherwise return to list of tasks again.

QP Hessian Matrix Validity

The MPC quadratic programming problem for optimal temperature control of an egg incubator obligation to have the single solution. Task should select the performance index parameters (penalty weights) and horizons such that the QP's hessian matrix was positive-definite. That means the Reccatti matrix was positive and solution was single. Therefore, QP optimal temperature control of an egg incubator solution satisfied the optimization of temperature problem solution.

Penalty weights on manipulated variable rates

By having guaranteed on positive-definite hessian by rising penalties on manipulated variable gradients of optimal temperature control of egg incubator. Its potential disadvantage was more sluggish in the controller response. The following table list in thesis controller least possible MPCobj.Weight.MVrate parameter for every MV.

Table 5.3 Penalty weights on manipulated variable rates

MV	Weights.MVRate
Q_i	10
T_in	5
Q_emb	10

So, finally the no badly-behaved penalty weight on manipulated in the MPC controller and no problem was detected.

Penalty weight on output variables

The output temperature of an egg incubator penalty weight also affect the hessian. Non-zero values were emphasized the significance of output temperature or variable (OV) target tracking and making the single QP solution more expected. The following table list the minimum weight for every OV along the prediction horizon and there is no problem founded.

Table 5.4 Penalty weights on output variables

OV	Weights.OV
T_out(1)	20
T_out(2)	100
T_out(3)	10

Horizon parameters for egg incubator with delay

If the egg incubator contains delay T , the prediction and control horizons (P and M) should be placed suitably. The last MV movement in the optimal temperature control order occur at step M . In order to affect the output temperature of an egg incubator system with-in the prediction horizon, the following state should be satisfied: $P - M > T$. Else, the last manipulated variables MV movement was irrelevant to output temperature or variable (OV) control and the QP might not have a unique solution. So, the maximum total delay in this thesis prediction model is $T = 0$ sampling periods, and $P - M = 8$. This shows that no problem sensed.

Scale Factor

Scaling translate the correlation between output temperature and operated variable of the egg incubator to dimensionless form. Scale factor objective criteria could improve QP numerical accuracy. These variables also make it easier to specify fine-tuning weight levels. In order to output temperature of egg incubator to be controllable, each parameter should respond at least one operated variable with-in prediction horizon.

If the egg incubator was better scaled, then the optimum absolute value of temperature of egg incubator was responses should be degree of unity. Output temperature of an egg incubator has maximum complete scaled responses were outside the range. The table shows the optimum absolute response of each such OV with respect to each MV. Because the third output of an egg incubator was zero.

Table 5.5 Scale factor

Q _i	Q _i	T _{in}	Q _{emb}
T-out(3)	0	0	0

Controller internal stability

An egg incubator was internally stable for all initial conditions, then bounded signal was injected with in egg incubator and all state of egg incubator remain bounded for all future time. A feedback of egg incubator improves such controller might nominally stable, but would execute poorly in exercise. This task extract matrix A from the unconstrained controller state-space realization and then computes its eigenvalues. If the absolute value was one or less than one or each eigenvalue was located in negative axis of the plane, then the designed optimal temperature controller was internally stable. So, the controller was satisfied all the sufficient condition and stable and the designed controller was internally stable.

Closed-loop nominal stability

The closed loop connection of the egg incubator and temperature controller could be stable for the nominal instance, once the controller prediction model signify the egg incubator perfectly and no constraint were active. This task gets the discrete time state space realization of the feedback the egg incubator and optimal temperature controller connected in closed loop arrangement. It removes from the A matrix and computes its eigenvalues at the nominal case (unconstrained) egg incubator system was stable and in this thesis the closed loop plant was nominally stable.

Closed loop steady state gain

Cloffset was used to regulate whether the controller pushes all controlled output temperature to their own target at steady state, in the absence of constraint. The command calculates the impact of a sustained disturbance on each measured output temperature in term of input or output gain. If a gain was zero, the controller minimizes steady state tracking error for that disturbance to output mapping.

Table 5.6 Closed-Loop Steady-State Gains

Disturbed output variable	Affected output variable	Gain
T_out(1)	T_out(1)	0.99599
T_out(2)	T_out(1)	-0.195955
T_out(1)	T_out(2)	-0.00182027
T_out(2)	T_out(2)	0.00579491
T_out(3)	T_out(3)	1

If this was not in thesis intent, the possible causes were as follows:

- Zero penalty weight on an egg incubator output. Check the Weights.OV property.
- Non-zero penalty weight on a manipulated variable. Check the Weights.MV property.
- State estimator that does not include integration of output tracking error. The default estimator includes integration. If we have modified or replaced it, review our estimator design.

Soft constraint ECR parameter

This task was evaluate the constraint ECR parameter to the controller achieve proper balance of using hard and soft constraint. If a constraint was too soft, an unacceptable violation might occur. Moreover, making the constraint harder couldn't prevent the violation if the constraint was fundamentally infeasible. It have defined 6 soft constraint and the table below list these and show potential violation based on defined variable bound and other factor.

Impact Factor of MPC performance index caused by this constraint violation relative to the average such increase. Sensitivity Ratio: the increase in the MPC cost function caused by this constraint violation relative to the typical cost function magnitude when there are no violations. It then estimated the impact of such violation on the MPC performance index relative to the impact of other violation. A bulky impact factor indicates a high priority controller objective, and vice versa. A sensitivity ratio

greater than $1e+08$ might degrade QP solution accuracy. In this thesis the sensitivity ratios were acceptable.

Table 5.7 Soft Constraints ECR Parameters

Constraint	Assumed Violation	Impact Factor	Sensitivity Ratio
Lower limit: T_out(2)	2	25	6.25e+04
Upper limit: T_out(2)	2	25	6.25e+04
Lower limit: T_out(3)	0.4	1	2500
Upper limit: T_out(3)	0.4	1	2500
Lower limit: T_out(1)	0.15	0.1406	351.6
Upper limit: T_out(1)	0.15	0.1406	351.6

5.9. COMPARISON BETWEEN MPC vs. PID CONTROLLER BASED ON RESULT

For MPC controller, the step response of incubator system presents no overshoot and rapid settling compared to PID controller. Figure 5.7 show the simulation results of the egg shell (skin) temperature and heat supply using PID controller respectively. In case of the MPC response of air temperature was increased rapidly to 37.4°C compared to PID controller. Unlike PID controller, the egg incubator have faster settling time and an un-desirable overshoot. In case of PID controller egg incubator system desirable transient response in term of steady state error, short rise time, short settling time and high overshoot. To find optimal parameters of PID controller tested by various parameters using Simulink and the better parameters were used. For MPC the sampling period, prediction horizon and control horizon were reasonable chosen of which provides the compromise between the degree of stability and plant performance. Finally MPC controller was best controller to handle MIMO system, achieve the desired performance and save the energy consumption.

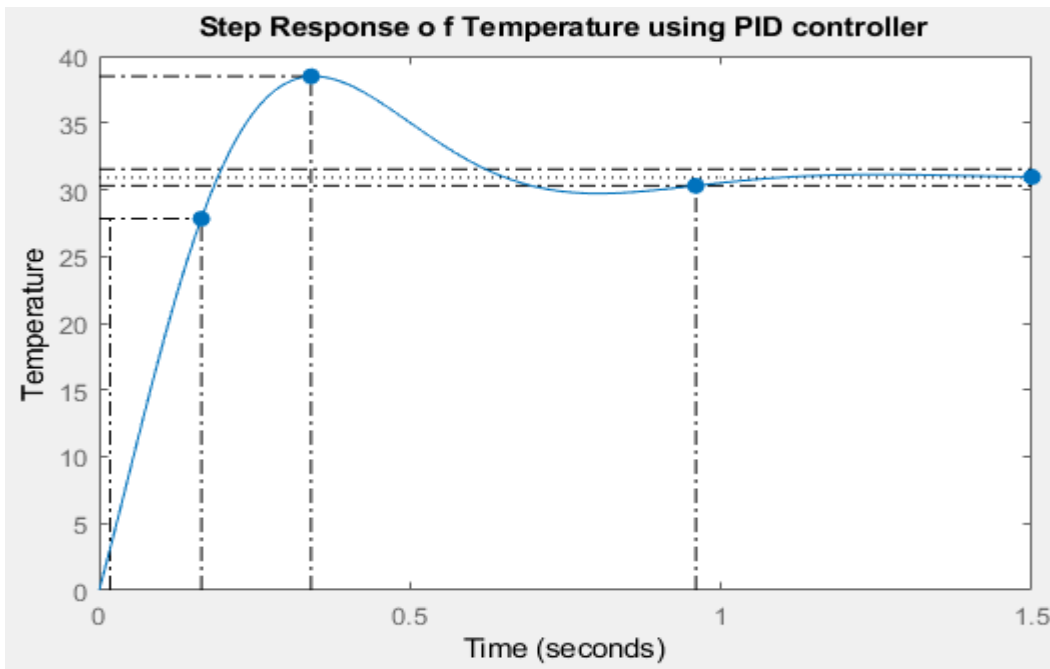


Figure 5.9 a) step response of egg shell temperature using PID controller

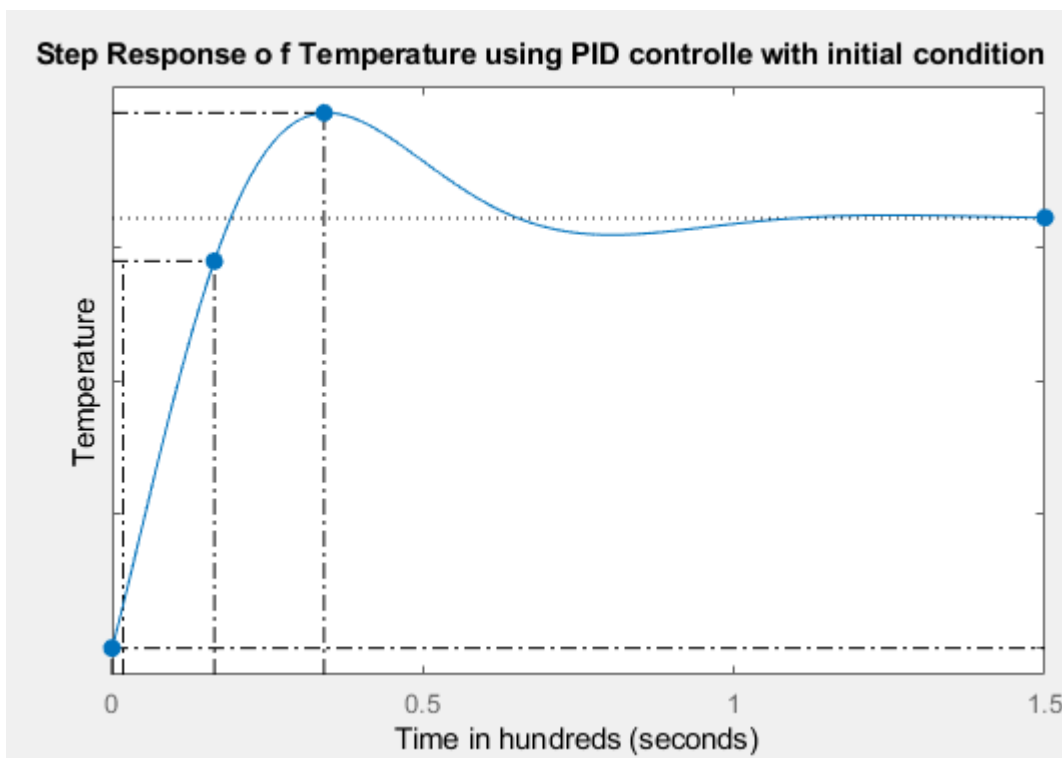


Figure 5.8.b) step response of temperature using PID controller with initial condition

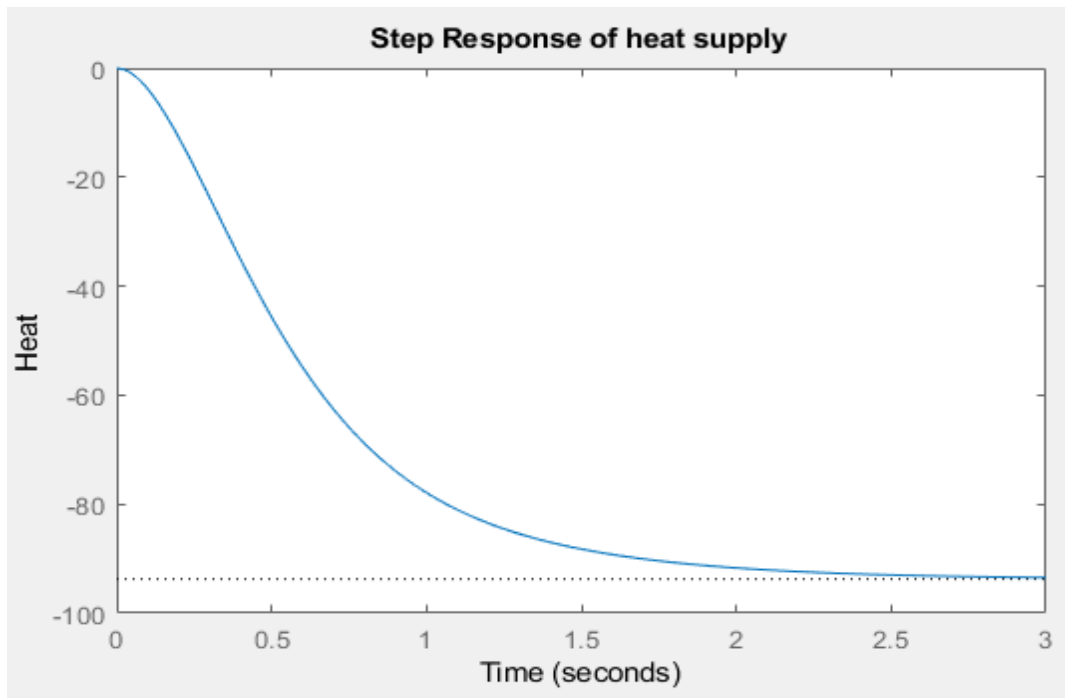


Figure 5.9. c) Step response of Heat supply using PID controller

In short numerical comparison presented in table 5.8 below.

Table 5.8 comparison result of PID controller and MPC controller

PID control parameter		MPC control parameter	
K_p	[3.52, -2.97, 0]	H_p (prediction control)	10
K_i	[14.5, -10.3, -1]	H_u (control horizon)	3
K_d	[0.0235, -0.208, 0]	T_s (sampling period)	0.5
Overshoot	[3.8, 0, 0]	Overshoot	No
t_r	[0.14, 1.2, 0]	t_r	0.3
t_p	[0.34, 2.5, 0]	t_p	0.5
t_s	[0.95, 2.63, 0]	t_s	0.8
Closed loop stability	Stable	Closed loop stability	Stable

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

In this thesis the design of optimal temperature controller for egg incubator using model predictive control was designed to control temperature of egg incubator system. The mathematical model of egg incubator system provides the means of generalizing the results and applying them to solving control and design problems of this particular nature. This egg incubator model also takes into account the thermal parameters of the structure of the egg incubator and egg. The environmental conditions was essential for the dynamic behavior of the egg incubator system to design optimal temperature control of egg incubator system using MPC. The important assumptions take to develop mathematical model of egg incubator. The stability of the optimal temperature control of an egg incubator system also verified through calculation, step response and code of MPC through Simulink simulations. The results should shows that the optimal temperature egg incubator system was stable and behaves as expected specifications. Simulation result shows that optimal temperature controller of egg incubator to achieve objective in shortest feasible instant with minimum overshoot, small rise time, small peak time and small settling time. These result on the thesis were proved that through MATLABTM Simulink model of egg incubator developed under the MPC was satisfactory. Based on the comparative analysis of these results it could be concluded that the optimal temperature controller for egg incubator system using MPC was satisfactory and its performance was accomplished. The initial egg shell air temperature assumed for simulation was 25°C. The controller specifications like settling time was improved in simulation by using MPC, the average may be close to 37.1°C, but deviation of over 0.4°C could be founded depending on embryonic age.

6.2 RECOMMENDATION

As the future work, the MPC and PID controller mechanisms will be developed to the commercial for the egg incubator with the calorimetric egg of hen. The future of MPC technology bright, with all of the vendors surveyed here reporting significant application in progress. Next-generation MPC technology is likely to include multiple performance index, infinite prediction horizon, nonlinear process models, better use of model uncertainty estimates, and better handling of ill conditioning.

Based on the findings and conclusions of thesis work will be recommended help the ministry of agriculture to set new strategic plan. In order to make the increase their product should develop the long term strategic plan that properly uses the output of poultry farm result for improvement and development of economic sustainable. In addition to the thesis findings to the thesis give some recommendation for the government of agriculture the Ethiopia specifically for the use of egg incubator poultry farm. And the findings of this thesis could be used as a source for the other thesis to be made related to this topic in the case of study optimal temperature control baby incubator by using MPC for healthy sector.

Finally, my recommendation this thesis will be best if it applied practically for both the industrializing the agriculturally sector to increase the farmers productivity by hatching egg by using egg incubator and also improve the safety problem of the human babies incubator in hospital to control its temperature at optimal level.

REFERENCE

- [1] N. S. Joseph, A. Lourens, and E. T. Moran, The effect of suboptimal eggshell temperature during incubation on broiler chick quality, live performance, and further processing yield, *Poultry Science*, 85(5) , 2006, 932-938.
- [2] D. J. Murray-Smith, *Methods of system identification, parameter estimation and optimization applied to problems of modelling and control in engineering and physiology*, doctoral, University of Glasgow, Glasgow, UK, 2009.
- [3] Mahmoud Salim, “Design and Implementation of a Digital Control Unit for the Oxygenaie Servo Baby Incubator”, *Journal of Power Electronics*, Vol. 8(2), April, 2008.
- [4] E. N. Hey and G. Katz, The optimum thermal environment for naked babies. *Arch Dis Child*, 45, 1970, 328-334.
- [5] E Feki, MA Zermani, A.Mami ‘‘GPC Temperature Control of A Simulation Model Infant-Incubator and Practice with Arduino Board ‘‘ *IJACSA*, 2017.
- [6] M. A. Zermani, E. Feki, A. Mami, “Application of Adaptive Predictive Control to Newborn Incubator”, *American J. of Engineering and Applied Sciences*, 4(2), 2011, 235-243.
- [7] D. W. Clarke, C. Mohtadi, PS. Tuffs, “Generalized predictive control: I. The basic algorithm”, Part I, *Automatica*, 23(2), 1987, 137-148.
- [8] M. Kubalcik, V. Bobal, “Predictive control of time-delay processes”, 26th European Conference on modelling and simulation, June 2012, Koblenz, Germany.
- [9] E Feki, MA Zermani, A Mami ‘‘ (*IJACSA*) *International Journal of Advanced Computer Science and Applications*’’, 8(6), 2017.
- [10] *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)* e-ISSN: 22781676,p-ISSN: 2320-3331, 10(6) Ver. II (Nov – Dec. 2015), 52-57 www.iosrjournals.org.
- [11] https://www.google.com/search?q=design+and+implementation+of+incubator+by+using+optimal+control+system.pdf&ei=uRs9WvbWDIXdwAL_2YfQAQ&start=120&sa=N&biw=1366&bih=674.
- [12] A.J. Lyon, M E Pikaar, P Badger, N McIntosh, “Temperature Control in Very Low Birth weight Infants During First Five Days of Life”, *Archives of Disease in Childhood Fetal and Neonatal Edition*, 76, November,1996, 47–50.

- [13] H. Gustavo, C. Oliveira, Luis. H. Ushijima, "A Hybrid Predictive Control Scheme for Hygrothermal Process", Proceedings of the 17th World Congress, the International Federation of Automatic Control, Seoul, Korea, July 6-11, 2008.
- [14] ML. Bernd Fischer, A. Meister, "The thermoregulation of infants: modeling and numerical simulation", BIT Numerical Mathematics, 41(5), 2001, 950-966.
- [15] D. W. Clarke, C. Mohtadi, PS. Tuffs, "Generalized predictive control: I. The basic algorithm", Part I, Automatica, 23(2), 1987, 137-148.
- [16] R. B. Abdenour, P. Borne, M. Ksouri, F. Msahli, "Identification et command numérique des procédés industriel", Paris, France: Eds. Technip; 2001.
- [17] Bequette B.W. "Process control modelling design and simulation" prentice hall edition.
- [18] Michael. H. LeBlanc, "Thermoregulation: Incubators, radiant warmers, artificial skins, and body hoods", 16 May 2018.
- [19] H. Gustavo, C. Oliveira, Luis. H. Ushijima, "A Hybrid Predictive Control Scheme for the Hygrothermal Process", Proceedings of the 17th World Congress, The International Federation of Automatic Control, Seoul, Korea, July 6-11, 2008.
- [20] R. D. Rojas, E. L. Dove, "A mathematical model of premature baby thermo-regulation and infant incubator dynamics", International Conference on Simulation Modelling in Bioengineering, 2005, 23.38.
- [21] MA Zermani, E Feki, A Mami - IRBM, "Building simulation model of the infant-incubator system with decoupling predictive controller", 2014.
- [22] Eduardo F. Camacho, Carlos Bordons Alba, second edition, "Model Predictive Control provides a thorough introduction to the theoretical and practical aspects of the most commonly used MPC strategies", 2013.
- [23] J. El Hadj Ali¹, E. Feki, A. Mami², (IJACSA) International Journal of Advanced Computer Science and Applications "Dynamic Matrix Control DMC using the Tuning Procedure based on First Order Plus Dead Time for Infant-Incubator" 10(6), 2019, 358, University of Tunis El Manar.
- [24] J. El Hadj Ali, E. Feki, M. A. Zermani, C. de Prada, A. Mami, "Incubator system identification of humidity and temperature: Comparison between two identification environments".
- [25] J.A. Rossiter, "Model-Based Predictive Control: A Practical Approach", 2003.

- [26] J Garcia-Hierro, JI Robla, P Barreiro, B Diezma... - International ..., "Design of a solar incubator. Part 1: monitoring temperature and enthalpy gradients under commercial production", 2012.
- [27] S Eren Özcan, S Andriessens, D Berckmans, "Computational study of the heat transfer of an avian egg in a tray", 2010.
- [28] J. Dostál L. Ferk¹, "Model Predictive Control of Climatic Chamber with On-of Actuators", Preprints of the 19th World Congress, the International Federation of Automatic Control Cape Town, South Africa, August 24-29, 2014.
- [29] Harb, S. K., Y. A. Habbib, A. M. Kassem, and A. EL Raies, "Energy consumption for poultry egg incubator to suit small farmer", 88 (1), 2010, Egypt. J. Agric. Res.
- [30] Mohd Badli Ramli^b, Hooi Peng Lim^b, Md Saidin Wahab^{a,*}, Mohd Faiz Mohd Zina^a on 2nd International Materials, Industrial, and Manufacturing Engineering Conference (MIMEC2015), "Egg hatching incubator using conveyor rotation system", 4-6 February 2015, Bali Indonesia.
- [31] Tawat Suriwong^{1,2,*}, Sathit Banthuek¹, Ekachai Singhadet¹ and Somchai Jiajitsawat³, "A new prototype of thermoelectric egg incubator integrated with thermal energy storage and photovoltaic panels", 11(02), 2017, 148-157, on Maejo Int. J. Sci. Technol.

APPENDIX

APPENDIX A

% Create a state-space model of an egg incubator system for optimal temperature control by % using model predictive control.

A = [0 2 -6;-2 -4 0;6 0 -6]; B= [2 -4 0;0 -2 0;0 0 -2]; C= [1 0 0; 0 0 1;0 0 0];

D= [0 0 0;0 0 0;0 0 0];

INCUBATOR = ss(A, B, C, D);

tf(INCUBATOR)

% mpc design task

Ts = 0.5; % the sample time

Hp = 10; % the prediction horizon

Hu = 3; % the control horizon

MPCobj = mpc(INCUBATOR,Ts);

mpcobj=mpc(INCUBATOR,Ts,Hp,H);

display(MPCobj)

mpcprops

get(MPCobj)

MPCobj.P = 15;

mpcobj.MV(1).Min = -0.05;

mpcobj.MV(1).Max = 1;

mpcobj.MV(2).Min = 0;

mpcobj.MV(2).Max = 3;

mpcobj.MV(3).Min = 0.05;

mpcobj.MV(3).Max = 2;

mpcobj.MV(1).RateMin = -0.02;

mpcobj.MV(1).RateMax = 0.5;

mpcobj.MV(2).RateMin = -0.2;

mpcobj.MV(2).RateMax = 1;

mpcobj.MV(3).RateMin = 0;

```

mpcobj.MV(3).RateMax = 0.5;
MPCOBJ.Field = 4
mpcobj.OV.Max = [1.1 1 0];
MPCobj.W
MPCobj.W.ManipulatedVariablesRate =[0.3 .1 0.2];
MPCobj.W.OutputVariables = [1 .8 0];
MPCobj.W.OutputVariables = [0.1 0 0;0.2 0 0;0.5 0 0;0 0 0];
review(MPCobj) T = 20; r = [36.5 37 0.25];
sim(MPCobj,T,r);      % the initial state plant
x_mpc = mpcstate(mpcobj); % Initial state of controller
r = [36.5 1 0.25];
%this simulates the closed-loop response for the duration of 20 control intervals with the set %point
%of % [36.5 1 0.25] for the first output (the air temperature), for second output (the egg shell
%temperature). Recall that the second output's tuning %weight is zero (see the %discussion in
Output Weights), so its set point is ignored.
MPCopts = mpcsimopt;
MPCopts.Constraints = 'on';
sim(MPCobj,T,r,MPCopts)
Plant = 1.5*INCUBATOR;
MPCopts.Model = Plant;
sim(MPCobj,T,r,MPCopts)
[y,t,u] = sim(MPCobj,T,r);
PerformanceWeights = mpcobj.weights;
plot(t,y)

```

APPENDIX B

%Code of MPC with constraint and optimal control

```
%Run the closed-loop simulation and save the results to workspace.
simopt.PlantInitialState = zeros(8,1,1);
[y,t,u,xp,xmpc]=sim(MPCobj,T,r)
[y,t,u,xp]=sim(MPCobj,T,r);
% Set constraints on manipulated variables, output variables and their rates of
%change.
    MPCobj.MV(1).Min = -2;
    MPCobj.MV(1).Max = 2;
    MPCobj.MV(2).Min = -1;
    MPCobj.MV(2).Max = 2;
    MPCobj.MV(3).Min = -0.5;
    MPCobj.MV(3).Max = 2;
    MPCobj.MV(1).RateMin = -4;
    MPCobj.MV(1).RateMax = 4;
    MPCobj.MV(2).RateMin = -2;
    MPCobj.MV(2).RateMax = 4;
    MPCobj.MV(3).RateMin = 0
    MPCobj.MV(3).RateMax = 4;
    %MPCobj.MO(1).Min = 0.5;
    %MPCobj.MO(1).Max = 2;
    %MPCobj.MO(2).Min = -1.5;
    %MPCobj.MO(2).Max = 2.5;
    %MPCobj.MO(3).Min =0;
    %MPCobj.MO(3).Max = 0.1;

%%
% Set weights on output variables.
MPCobj.Weights.OutputVariables = [1 1 0];
%%
% Set weights on the rates of manipulated variables.
MPCobj.Weights.ManipulatedVariablesRate = [.1 .1 .1];
%%
% Weights on manipulated variables remain as the default values [0 0 0].

%% Performance Evaluation Setup
% The default closed-loop performance is expressed through a set of weights
% that reflect the desired closed-loop behavior. The weights are contained
% in a structure with the same fields as the Weights property of an MPC
% object.
PerformanceWeights = MPCobj.weights;

%%
% In this thesis the output weights more important than weights on MV
% rates in evaluating closed-loop performance.
PerformanceWeights.OutputVariables = [100 100 0];
PerformanceWeights.ManipulatedVariablesRate = [1 1 1];
%%
% Note that "PerformanceWeights" is only used in the cumulated performance
% index computation. It is not related to the weights specified inside the
% MPC object.

%% Setup Simulation Options
% In this thesis, the only inspect the set point tracking scenario for the
```

```

% sensitivity analysis.
Tstop = 30; % time steps to simulate
r = ones(Tstop,1)*([1 1 1]);% set point signals
v = []; % no measured disturbance
options = mpcsimopt(MPCobj)
simopt = mpcsimopt;
simopt.PlantInitialState = zeros(8,1,1);
[y,t,u,xp,xmpc,SimOptions] = sim(MPCobj,T,r,v)
[y,t,u] = sim(MPCobj,T,r,v)
%%
%% Compute Sensitivities
[J1, Sens1] = sensitivity(mpcobj, 'ISE', PerformanceWeights, Tstop, r, v);
disp('')
disp('-----')
disp('Sensitivity analysis')
disp('-----')
disp('')
fprintf('Output weights: dJ/dWy = [%g, %g]\n',Sens1.OutputVariables);
fprintf('Input weights: dJ/dWu = [%g, %g, %g]\n',Sens1.ManipulatedVariables);
fprintf('Input-rate weights: dJ/dWdu = [%g, %g, %g]\n',Sens1.ManipulatedVariablesRate);
disp('-----')
disp('')

%% Adjust MPC Weights
MPCobj_new = MPCobj;

%%
% Sensitivity less than 0 suggests increasing output weight from 1 to 2.
MPCobj_new.Weights.OutputVariables(1) = 2;
%%

% Sensitivity greater than 0 suggests decreasing output weight from 1 to 0.2.
MPCobj_new.Weights.OutputVariables(2) = 0.2;
% no change Sensitivity.
MPCobj_new.Weights.OutputVariables(3) = 0;

%%
% Note that the sensitivity analysis only tells you which direction to
% change the parameters, not how much. Trial and error is expected.
%% Verify Cumulated Performance Index was reduced
% Recompute just the cumulated performance index using the same performance
% measure.
J2 = sensitivity(MPCobj_new, 'ISE', PerformanceWeights, Tstop, r, v);
fprintf('Previous Cumulated Performance Index J1 = %g\n',J1);
fprintf('New Cumulated Performance Index J2 = %g\n',J2);
%%
% Note that the absolute value of the cumulated performance index is not
% important.

%% Use a User-Defined Performance Function
% This is an paper of how to write a user-defined performance function
% used by the |sensitivity| method. In this paper, custom function
% |mpc_performance_function.m| illustrates how ISE performance index is
% implemented.

```

```

%
J3 = sensitivity(MPCobj, 'mpc_performance_function', Tstop, r, PerformanceWeights);
fprintf('User Defined Cumulated Performance Index J3 = %g (same as J1).\n', J3);

%%
displayEndOfDemoMessage(mfilename)
%%
%optimaization
Q = [100 0 0; 0 1 0; 0 0 1 ] ;
R = [1 0 0; 0 37.5 0; 0 0 0.5];
k= lqr(A,B,Q,R)
[k, P, E] = lqr(A,B,Q,R)

t = 0:0.01:8;
%[y,x,t] = step(AA,BB,CC,DD,1,t);
[y1, t1] = sim(MPCobj_new, Tstop, r, v);
[y2, t2] = sim(MPCobj_new, Tstop, r, v);
subplot(2,2,1)
plot(t2, r(:,1), t1, y1(:,1), t2, y2(:,1));
grid
title('Response y1 versus t (air temperature)')
xlabel('t Sec')
ylabel('y1')
subplot(2,2,2)
plot(t2, r(:,1), t1, y1(:,1), t2, y2(:,1));
grid
title('Response y2 versus t (skin temperature)')
xlabel('t Sec')
ylabel('y2')
subplot(2,2,3)
%plot(t,x)
grid
title('Response Curves x1, x2, x3, versus t')
xlabel('t Sec')
ylabel('x1,x2,x3')
text(2.6,1.35, 'x1')
text(1.2,1.5, 'x2')
text(0.6,3.5, 'x3')
u=(R^-1)*B*k; %optimal temperature controller

```

APPENDIX C

Infinite horizon linear quadratic regulator (LQR) algorism

```

%Create a state-space model of an INCUBATOR system.
A = [0 2 -6; -2 -4 0; 6 0 -6];
B = [2 -4 0; 0 -2 0; 0 0 -2];
C = [1 0 0; 0 0 1; 0 0 0];
D = [0 0 0; 0 0 0; 0 0 0];
Ts=0.5; % Sample time
x0 = [28; 25; 2]; % initial states at [28 25 2]
[Ap, Bp, Cp, Dp]=c2dm(A,B,C,D, Ts, 'zoh');
[m1, n1]=size(Cp);
[n1, n_in]=size(Bp);
R=0.1*eye(n_in, n_in); % Input weight: u'*R*y
Q=C'*C; % Output weight: y'*Q*y
INCUBATOR = ss(A,B,C,D);
sysd = ss(A,B,C,0, Ts); % Discrete-time system model

```

```

dcg = dcgain(sysd);           % DC-gain of prediction model
[K,P] = lqry(sysd,Q,R);      % LQR gain and Riccati matrix
cholP = chol(P); %Cholesky factor chol(P) of the Riccati matrix P
%Change and augment the output vector to include the full state x and yc: Output
= state vector x + output yc such that yc'*yc = x'*P*x
%sysd.C = [eye(3);cholP];
%sysd.D = zeros(3,1);
%sysd = setmpcsignals(sysd,'UO',[25 1 1]); % Cholesky factor is not measured
Hp = 3;                       % Prediction horizon (for any Hp>=1, unconstrained MPC
= LQR)
Hu = Hp;                       % Control horizon = prediction horizon
mpcobj = mpc(sysd,Ts,Hp,Hu); % MPC object
mpcobj.MV = struct('Min',{1,5,6},'Max',{25,25,10},'ScaleFactor',{5,5,2});
mpcobj.Weights.OV = sqrt(Q);   % Output weights (only on original output)
mpcobj.Weights.MV = sqrt(R);   % Input weight
mpcobj.Weights.MVRate = [1e-5 1e-5 1e-5]; % Very small weight on command
input increments
ry =[25 10 1];                % Output set point
%mpcobj.MV.Target = [25; 25; 25]; % Set-point for manipulated
variable
%Impose the terminal penalty x'(t+p)*P*x(t+p) by specifying a unit weight on
yc(t+p) = chol(P)*x(t+p). The terminal weight on u(t+p-1) remains the same, that
is sqrt(Qu):
Y = struct('Weight',[38 37 0]); % Weight on y(t+p)
u = struct('Weight',sqrt(R)); % Weight on u(t+p-1)
%setterminal(mpcobj,Y,u); % Set terminal weight y'*y = x'*P*x
setoutdist(mpcobj,'model',ss(zeros(3,1)));
setEstimator(mpcobj,[],eye(3)); % State estimate = state measurement
mpcgain = dcgain(ss(mpcobj));
fprintf('\n(unconstrained) MPC:
u(k)=[%8.8g,%8.8g]*x(k)',mpcgain(1),mpcgain(2),mpcgain(3));
fprintf('\n          LQR: u(k)=[%8.8g,%8.8g]*x(k)\n\n',-K(1),-K(2),-K(3));
if ~mpcchecktoolboxinstalled('simulink')
    disp('Simulink(R) is required to run this thesis.')
    return
end
rx = (eye(3)-dcg)\B/A;
r = [cholP*rx]; % Set point for extended prediction
model

%Simulate closed-loop control of the system model in Simulink. Controller
"mpcobj" was specified in the block dialog.

mdl = 'mpc_infinite';
open_system(mdl); % Open Simulink(R) Model
sim(mdl); % Start Simulation
%The closed-loop response shows good setpoint tracking performance.

```

```

bdclose('mpc_infinite');

```

APPENDIX D

%code for initial condition

```

A = [0 2 -6;-2 -4 0;6 0 -6];
B = [2 -4 0;0 -2 0;0 0 -2];
C = [1 0 0; 0 0 1];
D = 0;
Ts=0.5; % Sample time

```

```
x0 = [28;25; 2]; % initial states at [28 25 2]
sys = ss(A,[],C,[]);
initial(sys,x0)
```