Addis Ababa University

Addis Ababa Institute of Technology
School of Electrical and Computer Engineering

Integral Terminal Sliding Mode with Automatic Gain Tuning Fuzzy Logic Controller for Regulating Evaporator Superheat Temperature in HVAC Systems

A Thesis Submitted to the School of Graduate Studies, Addis Ababa University, for Partial Fulfillment of the Requirements for the Master of Science in Control Engineering

By Alemayehu Feyisa Debelo

October 2024

Addis Ababa, Ethiopia

Addis Ababa University Addis Ababa Institute of Technology School of Electrical and Computer Engineering

Integral Terminal Sliding Mode with Automatic Gain Tuning Fuzzy Logic Controller to Regulate Evaporator Superheat Temperature in HVAC Systems

A Thesis Submitted to the School of Graduate Studies, Addis Ababa University, for Partial Fulfillment of the Requirements for the Master of Science in Control Engineering

Advisor: Dr. Dereje Shiferaw

October 2024

Addis Ababa, Ethiopia

Declaration

I, the undersigned, declare that the work presented in this thesis is entirely original, has not been submitted for academic credit at this or any other institution, and is properly cited.

Alemayehu Feyisa Debelo

Name	**Signature**	**Date**

Email: **alemayehu.feyisa402@gmail.com**

Place: Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia.

This thesis has been submitted for examination with my approval as the university advisor.

Dr. Dereje Shiferaw

		01/03/25
Advisor	**Signature**	**Date**

Dedication

I dedicate this thesis to my family and friends, whose unwavering support has been instrumental throughout my Master's program and the writing process. Completing a master's and crafting this thesis is truly a collective endeavor; I am grateful for the community that helped me reach this milestone. Their love, encouragement, and invaluable feedback have shaped my research and writing skills, and I could not have achieved this without them. This work is a testament to their enduring presence in my life

Approval

The undersigned certifies that the thesis prepared by Mr. Alemayehu Feyisa Debelo, titled **“Integral Terminal Sliding Mode with Automatic Gain Tuning Fuzzy Logic Controller for Regulating Evaporator Superheat Temperature in HVAC Systems,”** and submitted as partial fulfillment for the Degree of Master of Science in Control Engineering, fulfills the regulations of the university and meets the accepted standards for originality, content, and quality.

Signed by Examining Board

Dr. Bisrat Derebssa		
Dean, School of ECE	**Signature**	**Date**
Dr. Dereje Shiferaw		01/03/25
Advisor	**Signature**	**Date**
Dr. Chala Merga		20.Jan.2025
Internal Examiner	**Signature**	**Date**
Yalemzerf Getnet		21.Jan.2025
External Examiner	**Signature**	**Date**
Dr. Lebsework Negash		
Chairperson	**Signature**	**Date**

Abstract

HVAC systems are inherently complex, and this complexity, along with various disturbances, makes it challenging to control the system effectively. Achieving a balance between meeting strict comfort requirements and minimizing energy use for optimal performance is particularly difficult. This thesis introduces a combined control strategy: the Integrated Terminal Sliding Mode Controller with Automatic Gain Tuning and Fuzzy Logic (ITSMC-FLAG). This controller regulates the superheat temperature at the evaporator outlet by adjusting the opening of the electronic expansion valve (EEV).

The ITSMC-FLAG controller efficiently manages both the evaporator superheat and evaporating temperature by adjusting the expansion valve's opening based on the superheat at the evaporator outlet and the inlet mass flow rates. It also takes into account the return room temperature and environmental uncertainties. This advanced approach not only enhances cooling performance and reduces energy consumption, but it also extends the lifespan of the compressor.

By combining terminal sliding mode control with fuzzy logic, the ITSMC-FLAG controller improves HVAC performance through a dynamic fuzzy logic auto-gain mechanism that adjusts the system's gains according to the current operating conditions. This ensures consistent and optimal performance, even with disturbances and fluctuations in system dynamics.

Comprehensive MATLAB simulations demonstrate the significant potential of the proposed controller to improve cooling efficiency, reduce energy consumption, and extend compressor life.

Keywords: *HVAC system, Integrated Terminal Sliding Mode, Automatic Gain Tuning, Fuzzy Logic Controller, Evaporator Outlet Superheat, Evaporating Temperature, Electronic Expansion Valve,*

Acknowledgments

I would like to begin by expressing my deep gratitude to Almighty God for the gift of wisdom, knowledge, and courage that guided me throughout this research journey.

I am especially grateful to my advisor, Dr. Dereje Shiferaw, for his invaluable guidance and support. His insights and encouragement have significantly enriched my work and provided me with essential lessons, and his advice was instrumental in the successful completion of this paper. I also want to acknowledge Dr. Yilma from the AAIT Mechanical Engineering Department for his crucial advice on HVAC systems, which played a vital role in my research.

Additionally, I extend my heartfelt thanks to my family, especially Mr. Gadise Hundera and my sons, who have been steadfast pillars of support during both joyful and challenging times.

Lastly, I am thankful to my brother for his unwavering support and to my friends for the wonderful moments we shared, all of which have profoundly shaped this journey.

Table of Contents

List of Figures

List of Tables

List of Acronyms

5G	Fifth Generation
AGT-FLC	Automatic Gain Tuning
AI	Artificial Intelligence
CUE	Carbon Usage Effectiveness
EEV	Electronic Expansion Valve
ESK	Extreme Seeking Controller
EPS	Epsilon
FLAG	Fuzzy Logic Automatic Gain
HVAC	Heating, Ventilation, and Air Conditioning
ILMPC	Iterative Learning Model Predictive Control
ITSMC	Integral Terminal Sliding Mode Controller
kg/m^3	Kilograms per cubic meter
kJ/kg	Kilojoules per kilogram
m	Rate of Mass Flow
PCS7	Process Control System 7
PUE	Power Usage Effectiveness
SMPT-1000	Smart Multi-Point Temperature Controller
STFLC	Self-Tuning Fuzzy Logic Controller
Tsh	Superheat Temperature
Tsheref	Superheat Temperature Reference
VCC	Vapour Compression Cycle
WUE	Water Usage Effectiveness
IT	Information Technology
ETC	Ethiopian Telecommunication Corporation
R22	refrigerant types R22
SFs	Scalar Factors

Chapter 1

Introduction

1.1 Historical Background of Cooling Solutions for Data Centers

The development of cooling solutions for data centers has been crucial to the growth and evolution of the information technology (IT) industry. In the early days of computing, mainframe computers generated little heat, and basic ventilation systems, relying mostly on fans and passive cooling methods, were sufficient to maintain the required operating temperatures. These simple systems effectively managed the lower heat outputs of early computing equipment. However, as IT hardware evolved in power and size, and as the demand for data processing and storage increased, the heat generated by these systems grew significantly. As a result, these basic cooling techniques became inadequate for maintaining the necessary operational conditions [1].

By the 1990s, the rapid expansion of the internet and the widespread adoption of personal computers led to a sharp rise in the number of data centers. The increasing need for data storage, processing, and reliability demanded higher-performing hardware and, consequently, more advanced cooling solutions. Traditional air conditioning systems, typically used to regulate temperature, became less effective as servers were densely packed into racks. This packed configuration resulted in higher energy consumption, elevated cooling costs, and greater environmental impact due to the rising energy requirements of these systems.

The early 2000s marked a major shift in cooling technologies, as data center operators began to adopt more advanced methods. Techniques such as hot and cold aisle containment, liquid cooling systems, and free cooling, which uses outside air to reduce energy costs, gained traction. These innovations addressed the challenges of cooling high-density equipment while reducing the operational costs associated with traditional HVAC systems. In the 2010s, the focus on energy efficiency intensified, driven by the need to lower operational expenses and meet sustainability goals. The global push for sustainability, coupled with the rising energy demands of data centers, propelled further research into more energy-efficient and environmentally friendly cooling technologies.

As energy efficiency became a top priority for data center operators, cooling systems, which account for up to 50% of a building's total energy consumption, received increased attention. Innovations in cooling technologies aimed to reduce energy use while maintaining optimal server conditions. Liquid immersion cooling, in which servers are submerged in thermally conductive liquids, and the integration of renewable energy sources for cooling, gained popularity as effective alternatives. These advancements not only provided more efficient thermal management but also helped meet the growing demand for sustainable operations within the data center industry. Moreover, the development of hybrid cooling systems that combine various methods to optimize energy use became increasingly common.

The cooling landscape has continued to evolve with the introduction of more sophisticated solutions, such as direct-to-chip liquid cooling, which addresses heat at its source, and more energy-efficient air-cooled systems. These innovations are particularly crucial as IT hardware continues to advance, generating even more heat due to the increasing power of processors, memory, and storage devices. The ongoing development of cooling technologies reflects the growing complexity of thermal management in modern data centers and highlights the ongoing need for advanced solutions to tackle the challenges of heat dissipation. As a result, efficient cooling will continue to play a critical role in the design and operation of future data centers, with sustainability and energy efficiency driving the need for innovation.

In Ethiopia, Ethio Telecom, the country's leading telecommunications provider, has been a key player in the modernization and development of the national communication infrastructure. Established in 2010 following the restructuring of the Ethiopian Telecommunications Corporation (ETC), which had monopolized the telecom sector since 1952,[2].

Ethio Telecom aimed to improve the efficiency, competitiveness, and service quality of Ethiopia's telecom services. As mobile communication and internet services grew in demand, EthioTelecom recognized the need to expand its infrastructure to meet the needs of an increasingly connected population, leading to a surge in the construction of data centers around 2010. As EthioTelecom's network grew and the demand for data services surged, the heat generated by an increasing number of network devices such as servers, routers, and switches became a significant challenge. To address this, the company implemented HVAC systems to regulate temperature and ensure the efficient operation of its growing infrastructure. However, these systems were initially deployed in data centers that were not optimized for energy efficiency, leading to higher energy consumption and increased maintenance needs. Over time, Ethio Telecom adapted its cooling strategies to improve the efficiency of its HVAC systems, making adjustments as the company's data center network expanded.
The evolution of cooling solutions in Ethio Telecom's data centers parallels broader trends in the global telecom and IT industries. The company's continuous modernization of its infrastructure, including the introduction of advanced cooling technologies, is part of a larger effort to enhance operational efficiency and reduce environmental impact. As Ethio Telecom continues to expand its services, including 3G, 4G, and 5G networks, as well as broadband internet, the importance of energy-efficient cooling solutions for its data centers remains crucial. These innovations are essential in ensuring that the company can meet the growing demands of Ethiopia's digital economy while minimizing its environmental footprint.

The adoption of advanced cooling technologies in Ethio Telecom's data centers reflects the increasing complexity of thermal management in modern telecom infrastructure. Driven by technological advancements, sustainability concerns, and the need for cost-effective solutions, these cooling innovations are in line with the broader trends in the global data center industry. As the telecom and IT sectors continue to evolve, the demand for energy-efficient and sustainable cooling technologies will remain vital to supporting the infrastructure needed for future growth [3].

1.2 Statement of Problems

Ethiotelecom's data centers and core sites face significant challenges in managing the thermal loads generated by their network infrastructure, relying heavily on air conditioning systems to regulate temperature. Due to the high density of equipment and poor rack organization, multiple air conditioning units are deployed to control the heat. However, the existing cooling systems control the electronic expansion valve (EEV) opening based solely on the return room temperature, leading to several operational issues.

A primary concern is that a large temperature difference between the return room temperature and the evaporator's superheat temperature can cause excessive refrigerant flow to the compressor, increasing power consumption and potentially damaging the system. On the other hand, a small temperature difference results in insufficient refrigerant supply to the evaporator, causing excessive superheating and reduced cooling performance. These issues lead to inconsistent temperature distribution, with compressors often running continuously in high-temperature areas, thereby escalating energy consumption.

Inadequate rack configurations at sites like Shashamanne worsen the problem by allowing hot and cold air to mix, which raises the return room temperature and leads to high superheat temperatures at the evaporator outlet. This reduces refrigerant efficiency and places excessive strain on the HVAC units, causing frequent compressor failures and costly replacements. Similar issues are also observed at other sites, such as Adama, Legar, and Kirkos, where improper sensor placement results in inaccurate readings, causing liquid refrigerant to return to the compressor, leading to further system damage and the need for multiple compressor replacements annually.

These challenges reveal the limitations of the current method for managing evaporator superheating, which is prone to significant temperature fluctuations and requires precise sensor placement. The existing system lacks scalability and does not effectively optimize cooling performance or reduce energy consumption. Therefore, there is a pressing need for a more efficient and precise control strategy that can optimize HVAC system operations, reduce energy consumption, and extend the lifespan of the equipment.

This paper proposes an Integrated Terminal Sliding Mode Controller (ITSMC) combined with Automatic Gain Tuning Fuzzy Logic (FLAG) to regulate the EEV opening based on the evaporator outlet superheat temperature. This approach aims to improve cooling efficiency, minimize energy consumption, and enhance the long-term performance of HVAC systems in Ethiotelecom's data centers.

1.3 Objective

The main objective of this thesis is to design and analyze an Integrated Terminal Sliding Mode Controller combined with an Automatic Gain Tuning Fuzzy Logic Controller for regulating the evaporator outlet superheat temperature in HVAC system.

1.3.1 Specific Objectives

- To formulate the mathematical equations for the evaporator and superheat temperatures in an HVAC system.
- To linearize the model of the electronic expansion valve by applying a linear approximation method to its nonlinear mathematical representation.
- To develop an Integrated Terminal Sliding Mode (ITSM) controller for regulating the superheat and evaporator temperatures in an HVAC system.
- To design an Integrated Terminal Sliding Mode (ITSM) controller combined with an Automatic Gain Tuning Fuzzy Logic Controller for smooth regulation of the superheat and evaporator temperatures in an HVAC system.
- To demonstrate the system's performance using MATLAB®/SIMULINK®.

1.4 Methodology

A. Developing a mathematical dynamic model of evaporator superheat and evaporating temperature for both steady-state and thermodynamic processes

B. The design integrates an external loop structure to effectively control the superheat temperature at the evaporator outlet by taking into account the evaporation rate and the inlet mass flow rate. This configuration produces the reference signal for the inner loops, which regulate the opening degree of the electronic expansion valve, ensuring the refrigerant remains as a slightly superheated vapor to prevent potential compressor damage and maintain efficiency.

C. The design of an internal loop structure for an integrated terminal sliding mode (TSM) controller based on fuzzy logic auto gain (FLAG) to control evaporating temperature and regulate inlet mass flow rates of refregirant gases into evaporator

D. implementing **Matlab simmulik**.

E. Analysis and interpretation the result and followed by recommendation

1.5 Thesis Organization

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

- Chapter 2 presents a literature review.
- Chapter 3: Developing a mathematical dynamic model of evaporator superheat and evaporating temperature for both steady-state and thermodynamic processes
- Chapter 4: Designing an Integrated Terminal Sliding Mode (TSM) controller combined with an Automatic Gain Tuning Fuzzy Logic Controller for both internal and external loops to simultaneously control evaporator superheat and evaporating temperature
- Chapter 5: Validation of the developed mathematical equations and the external and internal controllers, along with the simulation setup, results, application areas, and discussion
- Chapter 6 presents the conclusion, recommendation, and future work of the thesis

1.6 Significance of Research

This thesis makes notable contributions to control system design, focusing on achieving control objectives while minimizing energy consumption and response time. It investigates a control strategy that combines an Integral Terminal Sliding Mode Controller (ITSMC) with an Automatic Gain Tuning Fuzzy Logic Controller (AGT-FLC) to regulate the evaporating and superheat temperatures at the evaporator outlet. The main goal is to enhance cooling performance and energy efficiency while ensuring robustness against system uncertainties and external disturbances.

A key achievement of this work is the development of a dynamic model for the superheating and evaporating processes in the evaporator, derived from mass and energy conservation principles and heat transfer theory. This model effectively controls the superheat temperature to reach the desired setpoint. Additionally, a linearized model of the electronic expansion valve is introduced, based on its nonlinear mathematical representation, which is simplified using a linear approximation method. This linearized model enables more efficient regulation of the mass inlet flow rate to the evaporator, making it easier to meet control objectives. The integration of ITSMC with automatic gain-tuning fuzzy logic strengthens the system's robustness by merging integral control with terminal sliding mode control, allowing it to manage disturbances effectively. By utilizing an integral terminal sliding surface, ITSMC drives the system toward the desired equilibrium point in a defined time, minimizing response times and reducing chattering. This approach ultimately enhances both system performance and stability.

Chapter 2

Review of Literature

2.1 Introduction

According to [4], A Self-Tuning Fuzzy Logic Controller (STFLC) was developed to regulate the evaporator superheat temperature in a vapor compression chiller system, ensuring the desired temperature is maintained even with fluctuating refrigerant load conditions. The system utilizes an electronic expansion valve (EEV) as the control actuator. This paper presents the design and implementation of the STFLC for controlling evaporator superheat in a practical chiller system, specifically using R22 refrigerant. The STFLC automatically adjusts the EEV's opening to maintain the target superheat temperature, regardless of changes in refrigerant load.

The STFLC features an online tuning mechanism for output scaling factors (SFs), which adapts based on real-time process data. This dynamic adjustment improves system stability and efficiency by responding to varying conditions. Experimental results indicate that the STFLC outperforms conventional controllers, offering more reliable and efficient operation in response to changes in refrigerant load.

Accordingly [5] Gradient Descent for Near-Optimal Control and Extremum Seeking Control (ESC) to improve the control of superheat temperature in HVAC refrigeration systems. The first technique, Gradient Descent for Near-Optimal Control, focuses on analyzing the second derivative of the superheat temperature (T) relative to refrigerant mass flow at the evaporator outlet. This analysis guides the system to adjust T toward a near-optimal point, thereby enhancing overall system efficiency.

The second method, Extremum Seeking Control (ESC), employs a more sophisticated algorithm that goes beyond identifying a simple ”sweet spot” by targeting higher-order derivatives of superheat behavior. This enables ESC to precisely determine the minimum T value, which represents the optimal balance between system stability and performance. The system then automatically adjusts to this value, ensuring consistent, peak performance even under steady compressor speeds.

According to [6],Nonlinear Control and Disturbance Decoupling of an HVAC System via Feedback Linearization and Back-Stepping is applied for a nonlinear, MIMO HVAC System. Feedback Linearization, is used here to transform, the non-linear model of the HVAC system into a linear model by techniques called ”feedback liberalization. This involves introducing a special feedback loop with measurable states and disturbances, essentially ”tricking” the system into behaving like a linear one. The design method was applied to a MIMO and nonlinear model of an HVAC system and reached at the pre-specified goals of design such as output regulation and disturbance decoupling, which are apparent in simulations. Moreover, by this method a wide range of disturbance variations and zeroing the offset in the responses are achieved and identified.

according to [7], an iterative learning model predictive control (ILMPC) strategy is implemented to regulate the Superheat degree of the evaporator in a vapor compressor refrigeration cycle (VCC) system used in heating, ventilating, and air-conditioning (HVAC) systems. The control is achieved by adjusting the degree of opening of the expansion valve to maintain system stability and efficiency. The study considers a simplified model of the evaporator based on mechanism knowledge and system identification. Using the iterative learning theory and model predictive control method, an ILMPC controller is developed to regulate the superheat degree at the evaporator outlet. Simulation results are then conducted to validate the effectiveness of the proposed ILMPC controller. The output variable being controlled is the superheat degree of the evaporator, while the input variable is the opening of the expansion valve. The simulation verifies that the proposed control strategy can quickly and effectively drive the superheat degree to track its desired values. The future focus of the study will involve assessing the energy-saving performance of the system.

Accordingly [8] A novel online auto-tuning PI control algorithm is proposed in this work to adjust the evaporator outlet superheat temperature to the desired level. The proposed algorithm follows a systematic approach that includes two main steps. Firstly, a first-order plus dead-time model is employed to describe the system process. The model parameters are obtained through a robust identification algorithm using the online experimental data.

Secondly, a PI controller is designed to control the superheat at the outlet of the evaporator. The controller parameters are tuned using the Ziegler-Nichols method. The PI controller achieves control by adjusting the opening of the electronic expansion valve.

To assess the performance of the proposed algorithm, MATLAB simulations were conducted. The results demonstrate that the superheat can effectively track the change of its setpoint through the control of the electronic expansion valve.

Furthermore, the application of this controller has the potential to significantly increase the heat transfer efficiency of the evaporator. This improvement in efficiency surpasses that of conventional PID controllers.

According to [9],[10] Multi-Zone HVAC systems are complex, requiring precise control of temperature, humidity, pressure, and air quality while minimizing energy consumption and maintaining occupant comfort. This paper focuses on applying feedback linearization control methods to achieve these goals. Traditionally, individual zones are controlled based on their specific thermal loads. However, ignoring thermal interaction between zones can lead to inefficient operation. This paper presents a two-zone HVAC control system design that accounts for this interaction, modeled using physics and thermodynamics principles.

The impact of zone interaction on control effort and tracking error is analyzed through simulations using MATLAB/Simulink. The model considers two zones separated by a wall with known properties, demonstrating how their thermal exchange affects temperature tracking and control requirements.

This analysis highlights the importance of accounting for zone interaction in HVA system design, not only for improved efficiency but also for better performance customization based on wall material types. Furthermore, it paves the way for extending the approach to larger buildings with complex airflow dynamics, involving interconnected zones, air inlets, and outlets. This can significantly enhance HVAC system control and optimization.

According [11]. This paper analyzes the process flow of the Evaporator and utilizes the SMPT-1000 experimental Platform. The Evaporator functions as the control object with the goal of controlling the evaporator outlet flow, pressure, and temperature. The control method employed is Siemens PCS7, resulting in the design of a complete control system for the Evaporator. The control system was successfully operated for the Evaporator, showcasing the advantages of the predictive control algorithm presented in this paper. These advantages include high control accuracy, short adjustment time, and minimal overshoot for the temperature control system of the Evaporator. Additionally, the PID control algorithm enables on-line monitoring of the Evaporator's parameters. The results of the control process demonstrate that the proposal provided in the article can effectively meet production targets, possess industrial applicability, and achieve safety, energy-saving, and environmentally friendly control of the Evaporator.

Chapter 3

Mathematical Modeling of Evaporator Dynamics in HVAC Systems

3.1 Introduction

Evaporators are essential components of HVAC systems that absorb heat from air or other fluids and transfer it to the refrigerant. The refrigerant then carries this heat to the condenser, where it is released into the outside environment. Typically constructed from effective heat conductors like copper or aluminum, evaporators come in various shapes and sizes to accommodate different HVAC systems.[12],[13]

3.1.1 Working principle of HVAC sysem

A heating, ventilation, and air conditioning (HVAC) system is a network of devices that work together to regulate the temperature, humidity, and air quality in an inclosed area. HVAC systems are used in a wide variety of buildings, including homes, offices, schools, hospitals, data center and others. The basic working principle of an HVAC system is to transfer heat from one location to another. This is done using a refrigerant, which is a substance that can easily change state from a liquid to a gas and vice versa.

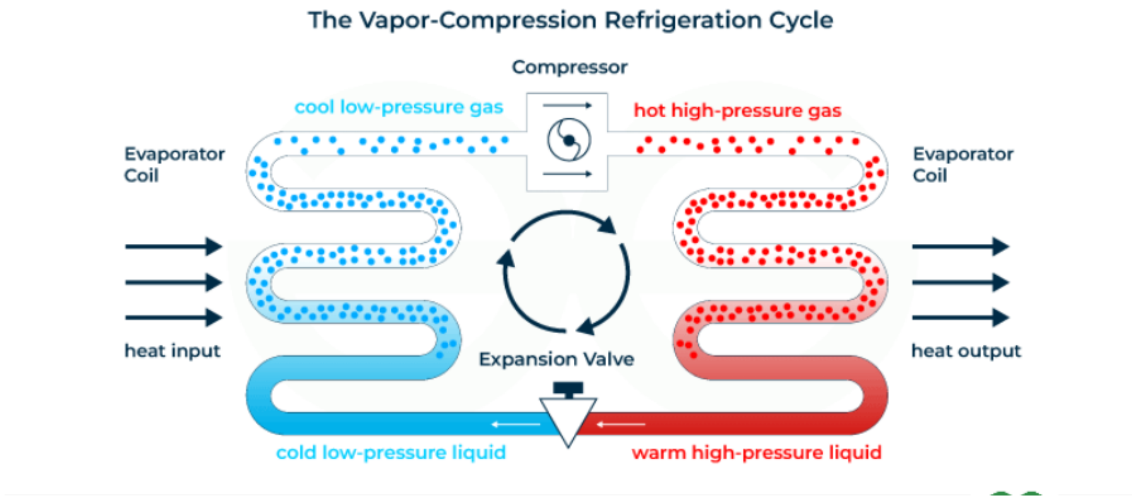


Figure 3.1: Dynamic Process and Refrigerant Circulation system

The refrigerant cycle has four basic processes, as shown in Figure 3.1. In the first process, low-pressure, low-temperature refrigerant enters the compressor at point 1 and then the compressor compresses the refrigerant, increasing its temperature and pressure at point 2. The high-temperature, high-pressure refrigerant then enters the condenser coil. A condenser fan blows air over the condenser coils, removing heat from the refrigerant and causing it to condense into a saturated liquid at point 3. The high-pressure, low-temperature refrigerant then passes through an expansion valve, which reduces its pressure and temperature at point 4. The expansion valve also regulates the flow of refrigerant to the evaporator coil. The evaporator blower fan blows chilled air into the home and absorbs heat energy from the home. In the evaporator, the liquid refrigerant vaporizes and superheats. The thermodynamic cycle then repeats itself [14],[15].

3.2 Mathematical Modeling of Evaporation, Superheating, and the Two-Phase Section in an Evaporator

The primary objective of this mathematical modeling is to demonstrate the impact of unregulated two-phase refrigerant gas states, superheat, and evaporating temperature on the cooling performance, energy consumption, and service lifespan of HVAC systems. Additionally, the model.

i. Describes the dynamic relationship between evaporating temperature and/or superheated temperature on the compressor-side mass flow rate, which can be further related to compressor speed. this implies that as the evaporating temperature decreases, the compressor-side mass flow rate decreases. This is because the refrigerant is less dense at lower temperatures, so the compressor has to work harder to move the same amount of refrigerant and

ii. Describes the dynamic relationship between the length of the two-phase section of an evaporator and the expansion valve-side mass flow rate, which can be further related to the determination of the expansion valve opening degree.

The two-phase section of an evaporator is a region where the refrigerant is in a mixture of liquid and vapor phases. Its length is determined by several factors, including the refrigerant mass flow rate, the evaporator inlet temperature, and the evaporator design. In generally the two-phase section of evaporator can be divided into two regions as shown in fig 3.2

- **Evaporating region**: This is the region where the refrigerant is actually vaporizing. The heat transfer coefficient in the evaporating region is typically high, as the refrigerant is absorbing heat and changing phase[16]
- **superheated region**: This is the region where the refrigerant has vaporized and is now superheated. The heat transfer coefficient in the superheated region is typically lower than in the evaporating region, as the refrigerant is no longer changing phase.[16]

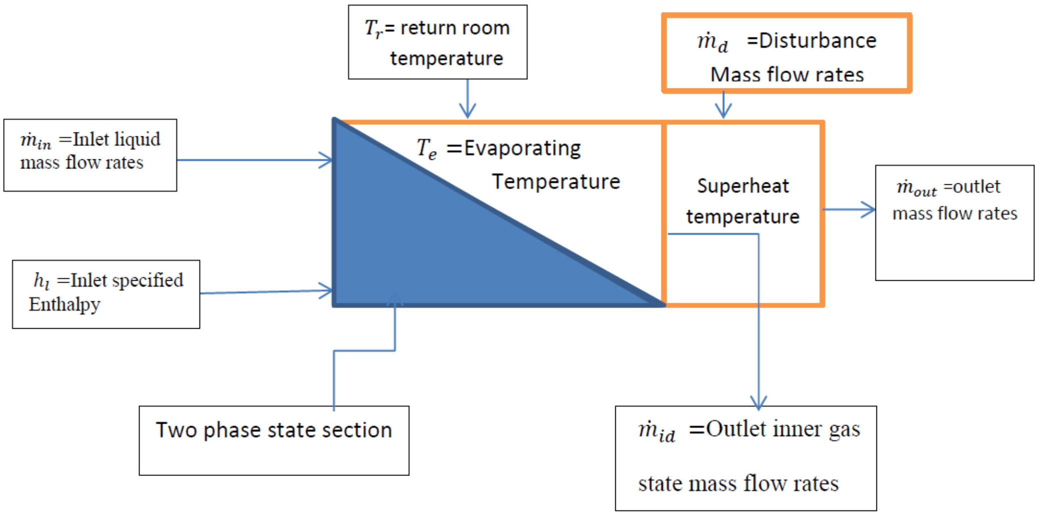


Figure 3.2: Dynamic Process In Evapoarator

.

3.2.1 Assumptions Taken

i. The homogeneous flow modeling method, its is a relatively very simple way to model the two-phase section of an evaporator. It assumes that the liquid and vapor phases are evenly distributed throughout the section.

ii. Refrigerant properties are assumed to remain constant

iii. Limiting the mass balance equation to the vapor mass to calculate the evaporating temperature.

iv , The degree of opening the Electronic expansion valve remains constant despite disturbances

v. the vapor quality of refrigerants is remain constant under any temperature

By applying the principles of mass and energy conservation, along with the energy transfer theorem, this thesis develops a comprehensive model of an evaporator in an HVAC system. This model allows for the effective regulation of evaporator superheat, mass flow rate, and evaporating temperature, ultimately resulting in enhanced cooling efficiency, optimized energy consumption, and extended compressor lifespan.

1. Mass balance equation for the two-phase section is given by

$$\frac{d}{dt}(D_l(1-\lambda)+D_g\lambda)Al(t)=\dot{m_{in}}-\dot{m_{id}} \tag{3.1}$$

2. The energy balance equation for the two-phase section is given by

$$\frac{d}{d(t)}(D_lh_l(1-\lambda)+D_gh_g)Al(t)=\dot{m_{in}}h_l-\dot{m_{id}}hg \tag{3.2}$$

Where

- D_l=is refrigerant density at liquid saturation point (kg/m3)
- D_g=is refrigerant density at vapour saturation point (kg/m3)
- $h_l =$ specific enthalpy of the saturated liquid refrigerant (kJ/kg)
- h_g=specific enthalpy of the saturated vapor refrigerant (kJ/kg)
- A=inner cross-sectional area of the evaporator heat exchange pipe (m²)
- $\dot{m_l}$=mass flow rate of refrigerant entering the two-phase section (kg/s)
- $\dot{m_g}$=mass flow rate of refrigerant leaving the evaporator (kg/s)
- $\lambda =$ is the void mean fraction; it is defined as the ratio of the volume occupied by the gas phase to the total volume of the flowing mixture

If we assume that the refrigerant properties do not change significantly over time and that there are no disturbances, then we can calculate the two-phase section length using equations (3.1) and (3.2).

$$\frac{d}{d(t)}(D_lh_l(1-\lambda)+D_gh_g)Al(t)-\frac{d}{dt}(D_l(1-\lambda)+D_g\lambda)Al(t)=\dot{m_{in}}h_l-\dot{m_{id}}h_g-(\dot{m_{in}}-\dot{m_{id}}) \tag{3.3}$$

$$D_l((h_l-h_g)\,A\frac{d}{dt}l(t)=q+m_{in}(h_l-h_g) \tag{3.4}$$

where $q =$ is the evaporator heat transfer rate. using the By heat transfer properties and characteristics.

$h_g - h_l = h_{lg}$

$h_l - h_g = h_{lg}(l - x_o)$

where $x_o =$ is vapour quality of of refrigerants, then equation (3.4) can rewritten as

$$D_l(1-\lambda)A\frac{d}{dt}l(t) = -\frac{q}{h_{lg}} + \dot{m_{in}}(1-x_o) \tag{3.5}$$

$$\frac{dl(t)}{dt} = -\frac{d\pi\alpha}{D_l h_{lg}(1-\lambda)A}(T_r - T_e)l + \frac{\dot{m_{in}}(1-x_o)}{D_l(1-\lambda)} \tag{3.6}$$

Let represent the coefficients as follow , this representation is only simplification

$$a_1 = -\frac{d\pi\alpha}{D_l h_{lg}(1-\lambda)A} \tag{3.7}$$

$$b_1 = \frac{(1-x_o)}{D_l(1-\lambda)} \tag{3.8}$$

Therefore, we can express equation (3.6)

$$\frac{dl}{dt} = a_1(T_r - T_e)l + b_1\dot{m}_{in} \tag{3.9}$$

3.2.2 Mathematical Modeling of Evaporating Temperature

Evaporating temperature is the temperature at which a refrigerant transitions from a liquid state to a vapor state. This occurs in the evaporator component of an HVAC system, where the refrigerant absorbs heat from the surrounding air, causing it to boil and evaporate. The evaporating temperature of a refrigerant is typically between 4°C and 5°C (39°F and 41°F). It is important to note that the evaporating temperature does not change with the room temperature. However, different refrigerants have slightly different boiling points based on their chemical composition. To derive an equation for the evaporating temperature (Te) of HVAC systems, we can use the mass balance equation for the vapor mass and considering that there is superheated temperature exists in the system, the inlet and outlet vapor mass flow rates are not equal and given by $\dot{m}_{in}x_o$ and $\dot{m_{out}}$ respectively. The rate of vapor generation from liquid to vapor is $\frac{q}{h_{lg}}$. The rate of change of the vapor mass in a system is equal to the difference between the inlet and outlet vapor mass flow rates, plus the rate of vapor generation from the liquid.

$$\frac{d}{dt}M = V\frac{d}{dT_e}D_g(T_e)\frac{dT_e}{dt} = \dot{m}_{in}x_o + \frac{q}{h_{lg}} - \dot{m_{out}} \tag{3.10}$$

where M_v , and V are the total vapor mass and total volume of the low-pressure side and T_e evaporating temperature, there fire by assuming that in the low-pressure side the vapour volume is much larger than the liquid volume.
let we consider that

$$Z = v\frac{d}{dT_e}D_g \tag{3.11}$$

$$\frac{d}{dT_e}D_g = z_1T_e + z_2 = Z \tag{3.12}$$

where
Where z_1, and z_2 are considered constants and depends on the refrigerant fluid characteristics, V is the inside volume of low pressure side, $\dot{m}_{out}$ is the mass flow rate of the refrigerant at the outlet of the evaporator

$$\frac{d}{dt}T_e = \frac{d\pi\alpha}{Zh_{lg}}(T_r - T_e) + \frac{\dot{m}_{in}x_o}{Z} - \frac{\dot{m}_{out}}{Z} \tag{3.13}$$

$$\frac{dT_e}{dt} = \frac{a_2(T_r - T_e)}{z_1T_e + z_2}l + \frac{\dot{m}_{in}x_o}{z_1T_e + z_2} - \frac{\dot{m}_{out}}{z_1T_e + z_2} \tag{3.14}$$

. where $a_2 = \frac{d\pi\alpha}{h_{lg}}$, T_e Evaporating temperature, d is inner diameter of copper pipes

3.3 Superheat Temperature in HVAC system

The superheat temperature is defined as the difference between the actual temperature of the refrigerant vapor exiting the evaporator and its corresponding saturation temperature at the same pressure. The saturation temperature is the temperature at which the refrigerant begins to condense into a liquid.

The superheat temperature serves as a key indicator of the evaporator's efficiency in heat absorption. A higher superheat temperature indicates that the evaporator is absorbing more heat, while a lower superheat temperature suggests less heat absorption. In HVAC systems, the ideal superheat temperature typically falls within the range of 5°C to 10°C (41°F to 50°F).
Let us use the gradient descent method to calculate the evaporator superheat. Suppose the superheat function $f(T_{sh}, T_r, l)$ is given by:

$$f(T_{sh}, T_r, l) = (T_{sh} - T_{sh,\text{target}})^2 + \lambda \cdot g(T_r, l)$$

The gradient of this function with respect to T_{sh}, combined with the refrigerant flow characteristics and superheat temperature, is given by:

$$\nabla_{T_{sh}} f(T_{sh}, T_r, l) = 2(T_{sh} - T_{sh,\text{target}})$$

$$T_{sh} = (T_r - T_e)\left(1 - e^{-\frac{C(L-l)}{\dot{m}_{out}}}\right) \tag{3.15}$$

where T_{sh} is superheat temperature, $C = \frac{d\pi\alpha}{C_p}$ and c_p is being the specific heat capacity of the refrigerants, L is length of evaporator and l is length of two phase section respectively.

3.4 State-Space Representation of the Evaporator System Model

The state-space equation of a modeled evaporator is a mathematical representation of the evaporator's dynamics in the form of a set of differential equations. These equations describe how the evaporator's state variables, such as evaporating temperature, superheat temperature, refrigerant mass flow rate, and enthalpy, change over time in response to inputs such as heat load and refrigerant mass flow rate.

Let us consider the general form of nonlinear state-space equations to represent the nonlinear modeled evaporator equation.[17]

$$\dot{x} = f(x) + g(x)u + \gamma s \tag{3.16}$$

$$[x_1, x_2]^T = [l, T_e]^T \tag{3.17}$$

This represents the system variables, where $u = \dot{m}_{in}$ is the input variable

$$y_1 = h_1(x_1, x_2) = T_{sh} \tag{3.18}$$

$$y_2 = h_2(x_1, x_2) = T_e \tag{3.19}$$

Where, y_1 and y_2 is superheated and evaporating temperature respectively

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \tag{3.20}$$

Then using equation (3.9) and (3.16) we can explain dynamic equation of modeled for evaporator as follow.

$$\dot{x}_1 = a_1(T_r - x_2)x_1 + b_1\dot{m}_{in} \tag{3.21}$$

$$\dot{x}_2 = \frac{a_2(T_r - x_2)x_1}{z_1x_2 + z_2} + \frac{b_2}{z_1x_2 + z_2}u - \frac{\dot{m}_{out}}{z_1x_2 + z_2} \tag{3.22}$$

$$y = (T_r - x_2)\left(1 - e^{\frac{C(L-x_1)t}{\dot{m}_{out}}}\right) \tag{3.23}$$

where

$$b_2 = \frac{x_o}{z} \tag{3.24}$$

$$\gamma_1 = b_1 \tag{3.25}$$

$$\gamma_2 = \frac{b_2}{z} \tag{3.26}$$

$$f_1 = \frac{a_1(T_r - x_2)x_1}{z_1x_2 + z_2} \tag{3.27}$$

$$f_2 = \frac{a_2(T_r - x_2)x_1}{z_1x_2 + z_2} \tag{3.28}$$

. Chapter 5 offers a detailed verification of the developed mathematical equations, which is essential for ensuring their accuracy and reliability in modeling the intended phenomena. The chapter outlines the verification process in depth, evaluating the validity and effectiveness of the equations through various scenarios

Chapter 4

Integrated Terminal Sliding Mode Control with Automatically Gain Tuning Fuzzy Logic Controller

4.1 Introduction

Heating, ventilation, and air conditioning (HVAC) systems are intricate networks that encounter numerous uncertainties and disturbances, leading to fluctuations in temperature, humidity, and airflow, especially in data centers. To address these challenges, this thesis presents an innovative control strategy that integrates Integral Terminal Sliding Mode Control (ITSMC) with an Automatic Gain Tuning Fuzzy Logic Controller (AGT-FLC).
The ITSMC method integrates integral control with terminal sliding mode control to enhance system robustness and effectively manage disturbances. By employing an integral terminal sliding surface, ITSMC directs system states toward a desired equilibrium point within a specified timeframe, thereby reducing response times and minimizing chattering.

A key feature of ITSMC is its integral component, which continuously accumulates error over time to rectify steady-state errors. This ongoing adjustment of the control input addresses any persistent discrepancies between the desired and actual system states. Compared to traditional HVAC control methods, ITSMC offers several advantages: it provides greater robustness against uncertainties and disturbances, making it well-suited for real-world applications where precise system models may be lacking. The design of the terminal sliding surface ensures quick and accurate convergence to the target control state.

Additionally, ITSMC eliminates the reaching phase typical of conventional sliding mode control, reducing chattering and enhancing the smoothness of control. The integral term in ITSMC guarantees zero steady-state error even in the presence of external disturbances, resulting in highly precise control performance

- Faster response
- Improved robustness to noise and disturbances
- Reduced chattering
- Minimize overshoot and undershoot
- While design complicity is considered as one of the limitation of ITSMC.

4.2 Control Design

The controller design consists of two loops, namely the external and internal loops, to regulate the evaporating and superheat temperatures of the Evaporator in an HVAC system

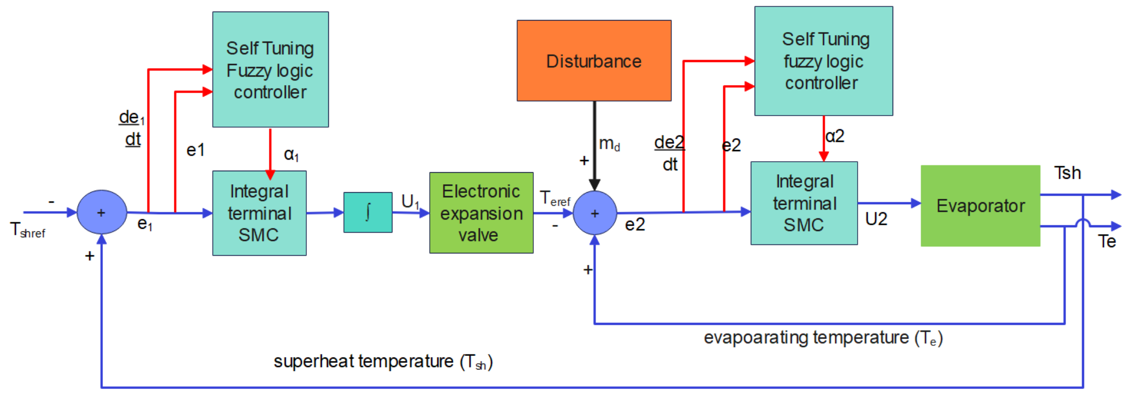


Figure 4.1: Control Block Diagram Integrating Terminal Sliding Mode Control and Automatic Gain Tuning Fuzzy Logic Controller

4.2.1 External Loop

The primary objective of the external control loop is to regulate the superheat temperature at the evaporator outlet while accounting for the incoming mass evaporation rate. This regulation aims to improve cooling performance, reduce energy consumption, and extend the lifespan of HVAC components, particularly the compressor. The superheat temperature at the evaporator outlet, where the refrigerant vapor exits, is critical for the compressor's efficiency and longevity. Maintaining this temperature within an optimal range is key to ensuring efficient HVAC operation and prolonging the system's overall lifespan.

An optimal superheat temperature strikes a balance between system efficiency, energy consumption, and compressor protection. Higher superheat temperatures ensure that the refrigerant is fully vaporized before entering the compressor, reducing the energy required for compression and enhancing overall system efficiency.

The electronic expansion valve (EEV) plays a crucial role in regulating the superheat temperature by controlling the refrigerant flow into the evaporator. Opening the EEV allows more refrigerant to enter, lowering the superheat temperature, while closing the valve restricts the flow, resulting in a higher superheat temperature.

In addition to its primary function, the external control loop also generates a reference signal for the internal loop, which manages the vaporization rate. This reference signal is essential for keeping the superheat temperature within the desired range at the evaporator outlet. The external control loop is therefore critical to system performance, continuously adjusting the EEV to maintain an effective balance between refrigerant flow and superheat temperature. In essence, the external control loop's main purpose is to generate the reference signal for the inner loop (vaporization rate) and ensure that the superheat temperature remains within optimal ranges at the evaporator outlet.

$$e_1 = T_{sh} - T_{shref} \tag{4.1}$$

and superheat temperature is predefined in Equation (3.15) as follows,

$$T_{sh} = (T_r - x_2)(\left(1 - e^{-}c(\frac{L - x_1}{\dot{mot}})\right) \tag{4.2}$$

.

by substituting equation (4.2) into equation (4.1), error e_1 is redefined as follow

$$e_1 = (T_r - x_2)\left(1 - e^{-}C(\frac{L - x_1}{\dot{mot}})\right) - T_{shref} \tag{4.3}$$

Where, T_r is return room temperature, x_2 is evaporating temperature, x_1 is superheat temperature in degree celcius, C is specific heat capacity,L is the length of evaporator and $\dot{m}_{out}$ refrigerants mass flow rate at outlet of evaporator

- By Defining an integral terminal sliding surface S_1, [18], [19]

$$S_1 = e_1 + \lambda_1 \int sgn(e_1)dt \tag{4.4}$$

Let us represent the the integral sliding surface part as follow

$$e_{1i} = \int sgn(e_1)dt \tag{4.5}$$

Therefore sliding surface S_1, can be re-described as follows

$$S_1 = (T_r - x_2)\left(l - e^{-}C(\frac{L - x_1}{\dot{m}ot})\right) - T_{shref} + \lambda_1 e_{1i} \tag{4.6}$$

.

First order derivatives of sliding surface $\dot{S}_1$

$$\dot{S}_1 = \dot{e_1} + \lambda_1 \dot{e_{1i}} = 0 \tag{4.7}$$

$$\dot{S}_1 = -\dot{x_2}\left(l - e^{-}C(\frac{L - x_1}{\dot{m}ot})\right) - C\frac{\dot{x_1}}{\dot{m}ot}(T_r - X_2)\left(e^{-}C(\frac{L - x_1}{\dot{m}ot)})\right) + \lambda_1 \dot{e_{1i}} = 0 \tag{4.8}$$

Let us redefine equation (4.7) to simplify and make it more suitable, as follows:

$$u = \dot{x_2} \tag{4.9}$$

$$\alpha_1 = \left(l - e^{-}C(\frac{L - x_1}{\dot{m}ot})\right) \tag{4.10}$$

$$\alpha_2 = -C\frac{\dot{x_1}}{\dot{m}ot}(T_r - X_2)\left(e^{-}C(\frac{L - x_1}{\dot{m}ot)})\right) \tag{4.11}$$

$\dot{S}_1 = 0$. so we can express as follow

$$\dot{S}_1 = -\alpha_1 u - \alpha_2 + \lambda_1 \dot{e_{1i}} = 0 \tag{4.12}$$

$$U_{eq1} = \frac{-\alpha_2 + \lambda_1 \dot{e_{1i}}}{\alpha_1} \tag{4.13}$$

Sliding mode control (SMC) is a robust control method that uses a combination of equivalent control and discontinuous control to ensure the system follows the desired sliding surface. Therefore, the discontinuity namely U_{dis} shall be calculated as follow

$$U_{diS1} = \frac{\beta_1 S_1 + \beta_2 sgn(S_1)}{\alpha_1} \tag{4.14}$$

overall control for external loop can be summarized as follow

$$U_1 = u_{eq1} + u_{diS1}$$

$$U_1 = u_{eq1} + u_{diSl} = \frac{-\alpha_2 + \lambda_1 \dot{e_{1i}}}{\alpha_1} + \frac{\beta_1 S_1 + \beta_2 sgn(S_1)}{\alpha_1} \tag{4.15}$$

$$U_1 = \frac{-\alpha_2 + \lambda_1 \dot{e_{1i}}}{\alpha_1} + \frac{\beta_1 S_1 + \beta_2 sgn(S_1)}{\alpha_1} \tag{4.16}$$

where, β_1 and β_2 are positive design parameters.
As outlined in the control block diagram, by integrating equation (4.16), we can compute the overall input signal for the electronic expansion valve and generate the reference signal for the inner loop.

$$G_1 = \int (U_1) dt \tag{4.17}$$

By substituting equation (4.17) into equation(4.18)

$$G_1 = \int \left(\frac{-\alpha_1 + \lambda_1 \dot{e_{1i}}}{\alpha_2} + \frac{\beta_1 S_1 + \beta_2 sgn(S_1)}{\alpha_2} \right) dt \tag{4.18}$$

Prove

By using a Lyapunov positive definite function, the global stability of the external loop designed controller can be improved as follows.[20]

$$V_1 = \frac{S_1^2}{2} \tag{4.19}$$

To guarantee its convergence, we must ensure that its derivative is negative.

$$\dot{V_1} = S_1 \dot{S_1} \tag{4.20}$$

By substituting equation (4.11) into equation(4.20)

$$\dot{V_1} = S_1\left(-\alpha_1\dot{G} - \sigma_2 + \lambda_1\dot{e_{1i}}\right) \tag{4.21}$$

By substituting U_1, mean that equation (4.16) into equation (4.21),

$$\dot{V_1} = S_1\left(-\alpha_1(\frac{-\alpha_2 + \lambda_1\dot{e_{1i}}}{\alpha_1} + \frac{\beta_1 S_1 + \beta_2 sgn(S_1)}{\alpha_1}) - \alpha_2 + \lambda_1\dot{e_{1i}})\right)$$

$$\dot{V_1} = S_1(\alpha_2 - \lambda_1\dot{e_{1i}} - \beta_1 S_1 - \beta_2 sgn(S_1) - \alpha_2 + \lambda_1\dot{e_{1l}})$$

$$\dot{V} = S_1(-\beta_1 S_1 - \beta_2 sgn(S_1)) \tag{4.22}$$

$$\dot{V} = -\beta_1\|S_1|^2 - \beta_2|S_1| < 0 \tag{4.23}$$

- since β_1 andβ_2 are positive parameters the Lyapunov function is satisfied and the convergence is guaranteed in finite time. Thus proving system stability

4.2.2 Inner Loop Designing

The primary goal of the internal loop controller is to regulate the evaporation rate by monitoring the refrigerant mass flow rate entering the evaporator. As the evaporation rate increases, the superheat temperature at the evaporator outlet rises, indicating the need for adjustments to the expansion valve to control refrigerant flow effectively. This adjustment is made through the electronic expansion valve (EEV), which controls refrigerant flow by modifying its opening. The EEV regulates refrigerant flow by varying its opening, which in turn adjusts the effective throat area of the valve. The optimal opening is determined by key factors, such as the superheat temperature at the evaporator outlet and the rate of refrigerant vaporization. By continuously adjusting its opening, the EEV responds to changes in the evaporator load, keeping the superheat temperature within the desired range and ensuring the system operates efficiently

4.2.3 Relationship Between Mass Flow Rate and Electronic Expansion Valve Opening Degree

According to [8], a linear design model for the valve head was developed to simulate the performance of an Electronic Expansion Valve in air conditioning systems. This design took into consideration the sub-segment flow characteristics of the conical valve head. A control strategy for the conical valve head was also proposed, utilizing these sub-segment flow characteristics. Simulation of performance curves for the multi-stage valve head in the air conditioning system included factors such as structural parameters and performance parameters like the refrigerant flow coefficient. Furthermore, analysis was conducted on the flow area of the electronic expansion valve and the refrigerant flow coefficient, with the calculation of the throat opening area of the electronic expansion valve using the equation below

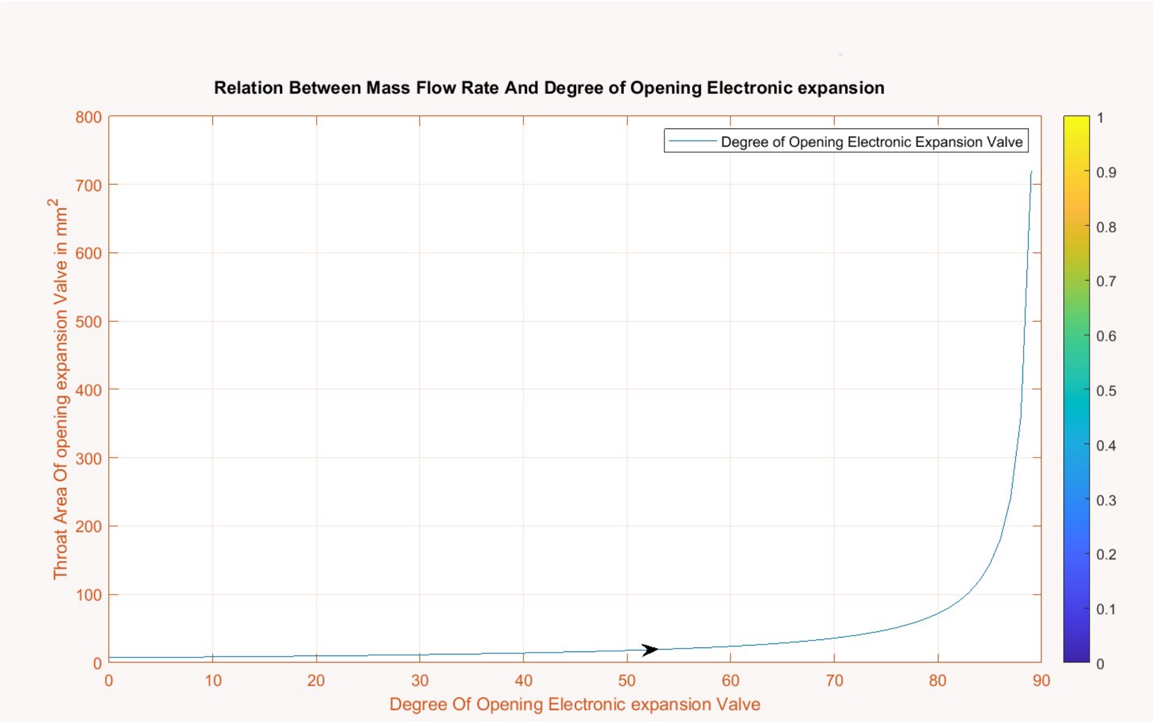


Figure 4.2: Mass flow Rate and Degree of Opening Electronic Expansion Valve Head

$$A_i = \frac{\pi h_i \sin(\theta_i/2)(d - h_i \sin(\theta_i/2) \cos \gamma_i)}{(\cos(\theta_i/2) - \sin(\gamma_i/2))} \tag{4.24}$$

- Where θ is the each segment angle of the valve head in the electronic expansion valve.
- h_i and D_i , are length, the diameter of the i segments valve, for $i = 1, 2, 3, - - -N$.

- γ is horizontal position angle
- A_i is throat opening area of electronic expansion valve for each segment.

For simply the complexity of designing, let we consider that the horizontal position angle γ, length h_i and diameter of opening expansion valve d_i are fixed value.
let $h_1 = 1$, $\gamma_i = 0$, $d_i = 3$,

$$A_i = \frac{\pi h_i \sin(\theta_i/2)(d - h_i \sin(\theta_i/2) \cos\gamma_i)}{(\cos(\theta_i/2) - \sin(\gamma_i/2))} \tag{4.25}$$

equation (4.25), can be rewritten as follow

$$A_i = \pi \tan(\theta_i/2)(3 - \sin(\theta_i/2)) \tag{4.26}$$

$$A_i = \frac{\pi h_i \sin(\theta_i/2)(d - h_i \sin(\theta_i/2) \cos\gamma_i)}{(\cos(\theta_i/2) - \sin(\gamma_i/2))} \tag{4.27}$$

equation (4.25), can be rewritten as follow

$$A_i = \pi \tan(\theta_i/2)(3 - \sin(\theta_i/2)) \tag{4.28}$$

In Figure 4.2, the diagrams show that increasing the opening degree and throat area of the electronic expansion valve (EEV) can lead to the risk of flooding the evaporator with liquid refrigerant, which could damage the compressor and reduce its efficiency. The EEV plays a critical role in regulating refrigerant flow into the evaporator. When fully open, it allows for maximum refrigerant flow; however, without proper control through superheat temperature feedback, an excess of refrigerant may flood the evaporator.

To maintain the superheat temperature within the ideal range of 5-10°C, it is essential to adjust the EEV opening based on factors such as the evaporator's length and load. Monitoring the superheat temperature is key to preventing flooding and optimizing system performance. By continuously tracking the superheat temperature and adjusting the EEV accordingly, the system can effectively control refrigerant flow. This approach ensures that too much liquid refrigerant does not enter the evaporator without adequate superheat control, thereby maintaining efficient cooling and protecting the compressor from potential damage.

To simplify the design complexity, it is recommended to express equation (4.24) as a tangential equivalent linear equation, using the tangential point for evaluation.[21]

let we consider that tangential point at $x = \frac{1}{3\pi}$

1. Evaluate , $f(x) = \pi\tan(x/2)(3 - \sin(x/2)$ at $x = \frac{1}{3\pi}$

$$f(x) = \pi\tan(\frac{1}{6\pi})(3 - \sin(\frac{1}{6\pi})$$

$$f(x) = f(a) = 4.53$$

2. Find the derivatives of $f(x)$ and Evaluate at $x = \frac{1}{3\pi}$

$$\frac{df(x)}{dt} = 3\pi/2(\sec(x/2)^2 - \pi(tan(x/2)cos(x/2))/2 + \pi(sin(x/2)sec^2(x/2))/2. \quad (4.29)$$

$$f(\dot{x}) = f(\dot{a}) = 4.82$$

3. Approximated linear equivalent equation is written as follow

$$l(a) = f(a) + f(\dot{a})(x - a) \quad (4.30)$$

$$l(a) = 4.53 + 4.82(x - 1.05)$$

$$y(x) = 4.82x - 0.53 \quad (4.31)$$

Since the evaporating temperature is defined in equation (3.14), the internal loop controller can be designed by expressing the evaporating temperature error e_2 as follows:

$$e_2 = \frac{a_1}{Z}(T_r - x_2)x_1 + \frac{b_2}{Z}m_{in} - \frac{\dot{m_{ot}}}{Z} - T_{eref} \quad (4.32)$$

where T_{eref} desired reference temperature for inner loop, and it can be calculated from equation (4.18) and (4.30)

$$T_{eref} = (4.82x - 0.53)(\int \left(\frac{-\alpha_2 + \lambda_2 \dot{e_{1l}}}{\sigma_1} + \frac{\beta_1 S_1 + \beta_2 sgn(S_1)}{\sigma_1}\right) dt)) \quad (4.33)$$

- By defining integral terminal sliding surface S_2 as follow,,[18],[19]

$$S_2 = e_2 + \lambda_2 \int sgn(e_2)dt \quad (4.34)$$

The first order derivatives of s_2

$$\dot{S_2} = \dot{e_2} + \lambda_2 \dot{e_{2l}} = 0 \tag{4.35}$$

By substituting equation (4.31) into equation (4.33), the sliding surface S_2 can be redefined as follows:

$$\begin{aligned} S_2 &= \left(\frac{a_2}{Z}(T_r - x_2)x_1 + \frac{b_2}{Z}m_{in} - \frac{\dot{m}_{ot}}{Z}\right) \\ &= (4.82x - 0.53)\left(\int \left(\frac{-\alpha_2 + \lambda_2 \dot{e}_{1l}}{\alpha_1} + \frac{\beta_1 S_1 + \beta_2 \sigma(S_2)}{\alpha_1}\right) dt\right) + \lambda_2 e_{2l} \end{aligned}$$

$$\dot{S_2} = -\frac{a_2}{Z}x_1\dot{x_2} + \frac{a_2}{Z}(T_r - x_2\dot{x_1} + \frac{b_2}{Z}\dot{m_{in}} - \dot{T_{teref}} + \lambda_2 \dot{e_{2l}} = 0 \tag{4.36}$$

Here we have inlet mass flow raters, m_{in} as control input and therefore sliding surface S_2 can rewritten as follow

$$u_2 = \dot{m_{in}} \tag{4.37}$$

$$\alpha_3 = \frac{b_2}{Z} \tag{4.38}$$

$$\alpha_4 = -\frac{a_2}{Z}x_1\dot{x_2} + \frac{a_2}{Z}(T_r - x_2)\dot{x_1} - \dot{T_{eref}} \tag{4.39}$$

$$\dot{S_2} = \alpha_3 u + \alpha_4 + \lambda_2 \dot{e_{2l}} = 0 \tag{4.40}$$

let us define that the overall U_2 as follow and where U_2 can be calculated by setting $\dot{s_2}$=0

$$U_2 = u_2 + u_{2i} \tag{4.41}$$

$$\dot{S_2} = \alpha_3 u_2 + \alpha_4 + \lambda_2 \dot{e_{2l}}$$

$$0 = \alpha_3 u_2 + \alpha_4 + \lambda_2 \dot{e_{2i}}$$

$$U_2 = \frac{-\alpha_4 - \lambda_2 \dot{e_{2i}}}{\alpha_3} \tag{4.42}$$

U_2 is obtained from equivalent equation.

$$U_{2i} = \frac{-\beta_3 S_2 - \beta_4 sgm(S_2)}{\alpha_4} \tag{4.43}$$

overall control for inner loop can be summarized as follow

$$U_2 = u_2 + u_{2i}$$

$$U_2 = \frac{-\alpha_4}{\alpha_3} - \frac{\lambda_2 \dot{e_{2l}}}{\alpha_3} + \frac{-\beta_3 S_2 - \beta_4 sgm(S_2)}{\alpha_3} \tag{4.44}$$

where, β_3 and β_4 are positive design parameters.

proof,By using a Lyapunov positive definite function, the global stability of the inner loop designed controller can be improved as follows.

$$V_2 = \frac{S_2^2}{2} \tag{4.45}$$

To guarantee its convergence, the first order derivatives of lypanov function should be negative

$$\dot{V_2} = S_2 \dot{S_2} \tag{4.46}$$

By substituting equation (4.40) into equation(4.46)

$$\dot{V_2} = S_2 \left(\alpha_3 U_2 + \alpha_4 + \lambda_2 \dot{e_{2i}}\right) \tag{4.47}$$

By substituting U_2 , from equation (4.47) into equation (4.497),

$$\dot{V_2} = S_2(\alpha_3(\frac{-\alpha_4}{\alpha_3} - \frac{\lambda_2 \dot{e_{2i}}}{\alpha_3} + \frac{-\beta_3 S_2 - \beta_4 sgn(S_2)}{\alpha_3}) + \alpha_4 + \lambda_2 \dot{e_{2i}})$$

$$\dot{S_2} = S_2(-\alpha_4 - \lambda_2 \dot{e_{2l}} - \beta_3 S_2 - \beta_4 sgn(S_2) + \alpha_4 + \lambda_2 \dot{e_{2i}})$$

$$\dot{V_2} = S_2(-\beta_3 S_2 - \beta_4 sgn(S_2)) \tag{4.48}$$

$$\dot{V_2} = -\beta_3 \| S_2|^2 - \beta_4 |S_3| < 0 \tag{4.49}$$

Therefore its confirmed that for any positive β_3 and β_4, Lyapunov function is satisfied and the convergence is guaranteed in finite time. Thus proving system stability

4.3 Automatic Gain Tuning Fuzzy Logic controller Design

An Automatic Gain Tuning Fuzzy Logic Controller (AGT-FLC) is an advanced fuzzy logic controller that automatically adjusts its parameters to ensure optimal performance without manual intervention[22]. This self-tuning feature enhances the HVAC system's adaptability and robustness, allowing it to adjust seamlessly to variations in system load or environmental conditions.

In this application, the controlled variable is the superheat temperature at the evaporator outlet. Superheat temperature indicates how much the refrigerant's temperature exceeds its saturation point. Continuous monitoring of this temperature is essential for maintaining system stability and efficiency. To regulate the superheat temperature, the manipulated variable is the opening percentage of the Electronic Expansion Valve (EEV). The EEV is crucial for maintaining the desired superheat temperature, ideally within the range of 5-10°C. This range is essential for optimizing cooling efficiency and ensuring the HVAC system operates smoothly.

4.3.1 Function

In the design of an automatically tuned fuzzy logic controller for the external loop, two inputs and a single output are defined. The first input is the superheat temperature error, which reflects the difference between the desired and actual superheat values. The second input is the derivative of this error, which captures its rate of change over time. The output controls the degree to which the expansion valve should be opened, thereby regulating the flow of refrigerant into the evaporator. T_{sh}. T_1 represents the sampling time in seconds, which is set 10 second for this simulation, while T_{shref} represents the set point temperature in degrees Celsius. The error at time k is represented as e_k, and the error at time $k-1$ is represented as e_{k-1} in degrees Celsius, respectively. The inputs are categorized as fuzzy error E_1 and fuzzy derivative of error DE_1, while the output is referred to as the fuzzy control signal T_{sh}. These linguistic variables are further divided into three fuzzy classes: negative small (NS1), zero (ZE1), and positive small (PS1). Triangular functions are used as membership functions to define these linguistic variables, with a normalized universe of discourse over the interval $[-1, 1]$ as shown in Fig 4.3.

Additionally, the auto-tuning algorithm incorporates a gain updating factor, denoted by σ_1.

This factor exists within the range $[0, 10]$ and is expressed as a linguistic variable with three fuzzy sets: zero (Z1O), small (S1), and big (B1).

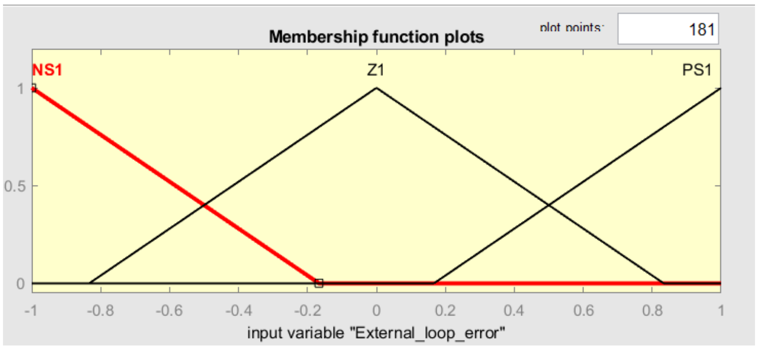


Figure 4.3: Membership Function for external Loop

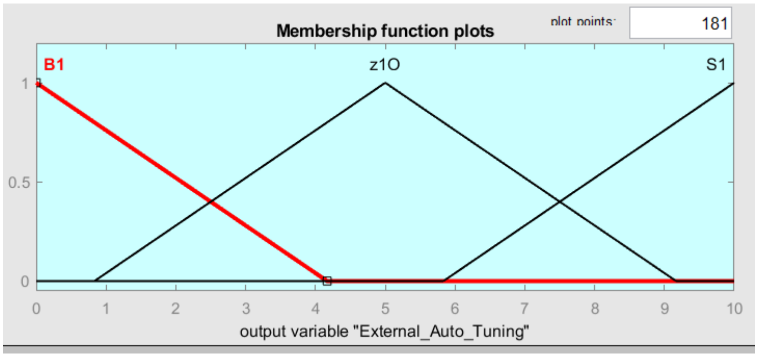


Figure 4.4: Membership Function for External Loop Update Factor σ_1

Table 4.1: Fuzzy Rules For External loop σ_1

σ_1	E_1			
DE_1		NS1	Z1	PS1
	NS1	B1	S1	Z1O
	Z1	S1	Z1O	B1
	PS1	Z1O	S1	B1

4.3.2 Membership Functions for inner Loop

In designing an automatically tuned fuzzy logic controller for the inner loop, similar to the automatic tuning used in the external loop, two inputs and a single output are defined. The first input, known as the evaporating rate error, represents the difference between the actual and desired evaporating rates. The second input is the derivative of this error, which captures how the difference changes over time. The controller's output corresponds to the level of the evaporating rate of the refrigerant's inlet mass flow

$$e_2 = T_e - T_{eref} \tag{4.50}$$

$$de_2 = \frac{e_k - e_{k-1}}{T_2} \tag{4.51}$$

The evaporating rate of the inlet mass flow, measured as the temperature at the evaporator outlet in degrees Celsius, is denoted as T_e. T_2 represents the sampling time in seconds, which is set to 5 seconds in this simulation, while T_{eref} represents the setpoint temperature in degrees Celsius. The error at time k is represented as e_k, and the error at time $k-1$ is represented as e_{k-1}, both in degrees Celsius.

The inputs are categorized as fuzzy error E_2 and fuzzy derivative of error DE_2, while the output is referred to as the fuzzy control signal. These linguistic variables are further divided into three fuzzy classes: negative small (NS2), zero (ZE2), and positive small (PS2). Triangular functions are used as membership functions to define these linguistic variables, with a normalized universe of discourse over the interval $[-1, 1]$ as shown in fig 4.3

Additionally, the auto-tuning algorithm incorporates a gain updating factor, denoted by σ_2. This factor lies within the range $[0, 10]$ and is expressed as a linguistic variable with three fuzzy sets: zero (Z2O), small (S2), and Big (B2).

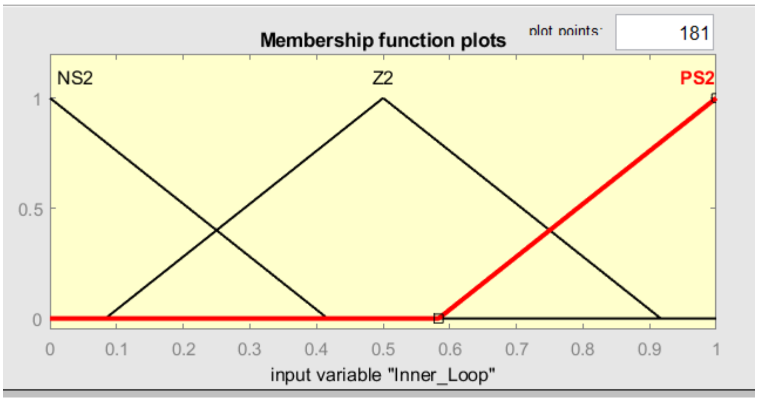


Figure 4.5: Membership Function for Inner Loop of σ_2,E_2,DE_2

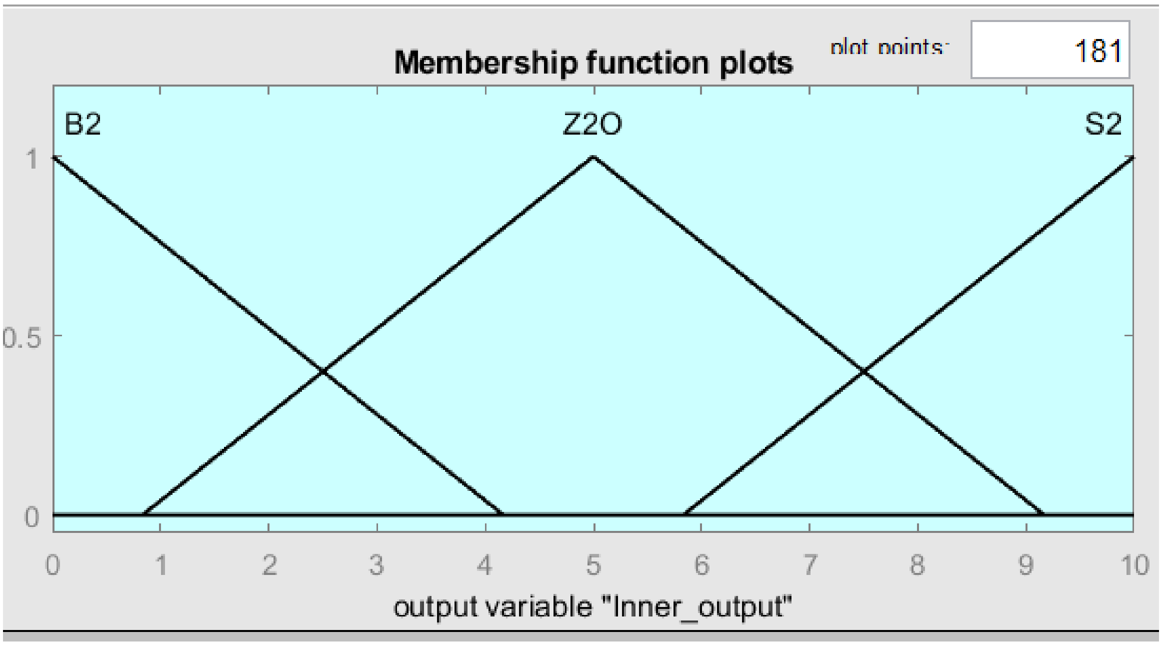


Figure 4.6: Membership Function of Inner loop Update Factor of σ_2

Table 4.2: Fuzzy Rules For Inner loop E_2,DE_2, σ_2

σ_2	E_2			
DE_2		NS2	Z2	PS2
	NS2	B2	S2	Z2O
	Z2	S2	Z2O	B2
	PS2	Z2O	S2	B2

Chapter 5

Simulation Results and Discussion

5.1 Dynamic Simulation of a Modeled Evaporator

In Chapter 3, the evaporator dynamics are modeled based on mass and energy conservation principles, alongside energy transfer theories. Key factors such as evaporation rates, superheat temperature, and the behavior of two-phase sections are discussed in detail. Similarly, Chapter 4, particularly in Figure 4.2, examines the relationship between mass flow rates and the electronic expansion valve's opening degree. It presents a linear design model for the valve head, simulating its performance in air conditioning systems by considering the flow characteristics of the conical valve head.

The dynamics of both the evaporator and the electronic expansion valve opening are represented using a MATLAB function block. This approach allows for the verification of the modeled dynamics under various conditions, emphasizing the significance of analyzing heat transfer and mass flow dynamics in the evaporator while accounting for different influencing factors

5.2 Simulation Parameters of HVAC system

In Table 5.1, the parameter specifications used for MATLAB simulation are presented. The table details the parameter specification for the Evaporator and Electronic Expansion Valve model simulation

Table 5.1: Parameters in HVAC Systems

Parameter	Value	Units
Inside Diameter	0.0081026	m
Cross Section Area	0.00005156	m^2
Refrigerant Enthalpy Difference	105.9	kJ/kg
Refrigerant Density	1300	kg/m^3
Mean Void Fraction	0.93	-
Ambient Temperature	27	°C
Vapor Quality	0.2	-
Length of Evaporator	11.5	m
Internal Volume	0.0028665	m^3
Refrigerant Mass Flow Rate	0.00713	kg/s
Fluid Characteristics Z_1	0.0368	-
Specific Heat Capacity of Refrigerants C_1	1	J/(kg·K)

5.3 Model Verification

To verify the model of the evaporator dynamics, particularly focusing on superheat temperature, evaporating temperature, the two-phase section, and the degree of opening of the electronic expansion valve (EEV), we will analyze the system by varying the return room temperature as a unit step input. Additionally, we will examine different scenarios with varying degrees of EEV opening. This evaluation technique entails implementing a step input to analyze the dynamic behavior of the electronic expansion valve's opening, illustrated in a MATLAB function block diagram in Figure 5.1

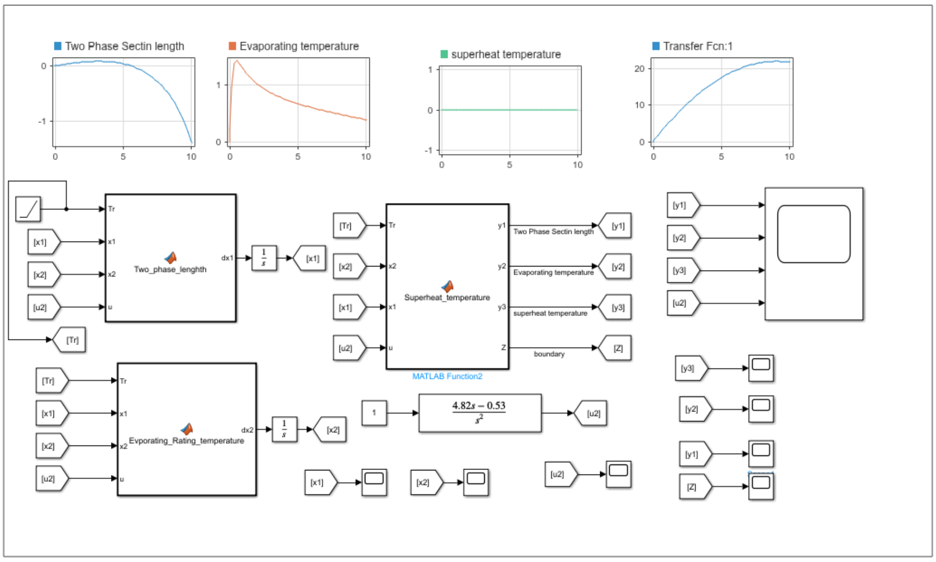


Figure 5.1: Open Loop Simulink Block Diagram

5.4 Evaluating Evaporator Performance Under Liquid Overflood Conditions for Model Validation

A large volume of liquid entering an evaporator results in increased energy consumption, reduced component lifespan, and lower performance. Assessing the evaporator's performance under these conditions is essential for understanding their impact on energy usage, cooling efficiency, and component durability. This paper aims to address the challenges of overflooding and reduce its negative effects. As a result, system operators can enhance performance, lower operational costs, and extend the lifespan of critical components. While managing overflood conditions typically requires regular maintenance, optimized design, and advanced control strategies, this paper focuses specifically on control strategy solutions

5.4.1 Verification of Evaporator Performance Using Equivalent Cross-Sectional Areas for Two-Phase and Evaporating Sections

In a continuously operating evaporator, maintaining a balance in heat transfer rates between the heat source, refrigerant, and evaporator load is essential. This balance relies on the proper flow of refrigerant into and out of the system, which is crucial for efficient operation. If the electronic expansion valve remains stuck open while the compressor is running, it may signal a malfunction that disrupts the regulation of refrigerant flow.

Problems can also occur when the reference temperature is set for a warmer environment, but the ambient temperature around the evaporator falls below the evaporation temperature. This mismatch can result in continuous refrigerant circulation without proper evaporation. Additionally, if the evaporator fan speed is inadequate, combined with significant condensation and a low thermal load in the surrounding area, the evaporative process may be compromised, leading to reduced cooling system efficiency. The superheat temperature of the evaporator is described in Chapter 3, specifically in Equation 3.15, as follows.

$$T_{sh} = (T_r - x_2)\left(1 - e^{-\dfrac{C(L - x_1)}{\dot{m}_{out}}}\right)$$

$x_1 = x_1$ implies that $L = l$

$$e^{-\frac{C(l-x_1)}{\dot{m}_{out}}} = 1$$

$$Y = T_{sh} = (T_r - x_2)\left(1 - e^{-\frac{C(L-x_1)}{\dot{m}_{out}}}\right) = 0$$

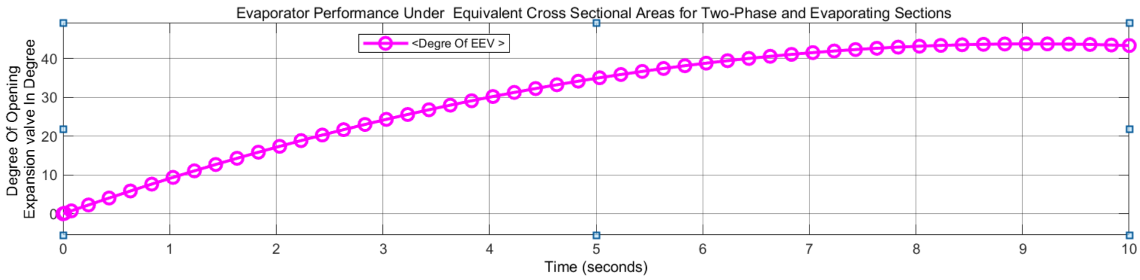


Figure 5.2: Degree of Opening of the EEV Under Conditions of Equally Distributed Two-Phase Flow and Evaporation Section

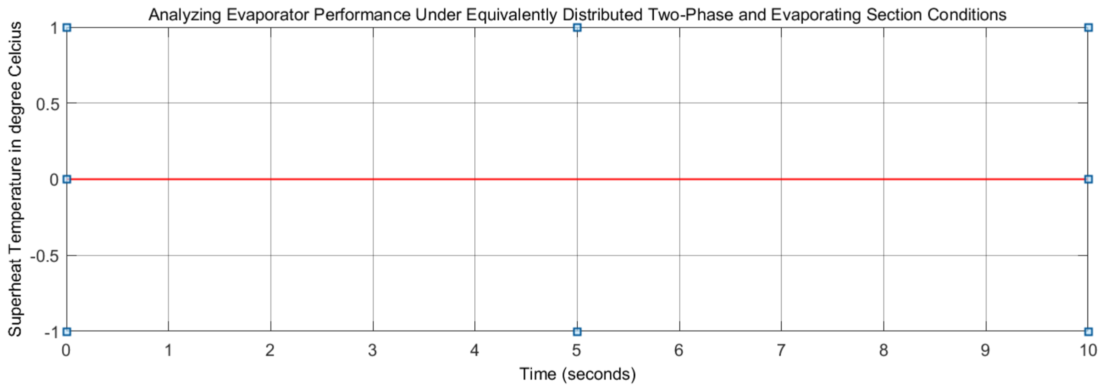


Figure 5.3: Superheat temperature Under Conditions of Equally Distributed Two-Phase Flow and Evaporation Section

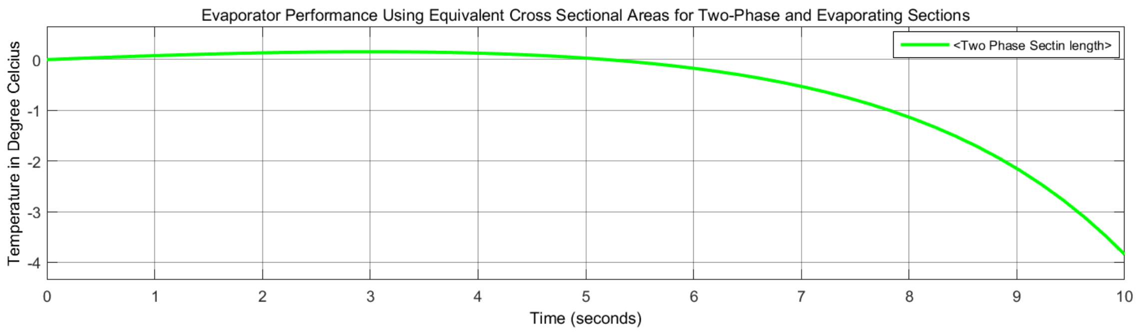


Figure 5.4: Two-Phase Section Under Conditions of Uniformly Distributed Two-Phase Flow and Evaporating Section

As illustrated in Figures 5.2 and 3 when there is a uniformly distributed two-phase flow within the evaporator section, increasing the opening of the electronic expansion valve results in a decrease in the superheat at the evaporator outlet, eventually reaching zero. This indicates incomplete evaporation of the refrigerant within the evaporator, as reflected in the cross-sectional area of the two-phase and evaporating sections. Insufficient evaporation can severely reduce the efficiency of the cooling system, particularly affecting the compressor. Operating with zero superheat increases the risk of liquid refrigerant entering the compressor, which can lead to damage and a shortened lifespan. This condition may also cause issues such as liquid slugging, increased wear on the compressor, and costly repairs or replacements.

Furthermore, zero superheat leads to higher energy consumption, as the system must exert more effort to achieve the desired cooling effect. This not only drives up electricity costs but also puts additional strain on system components, ultimately reducing overall energy efficiency. Low superheat levels can adversely affect cooling performance and heat transfer efficiency, leading to uneven or insufficient cooling, which undermines the system's reliability and cost-effectiveness

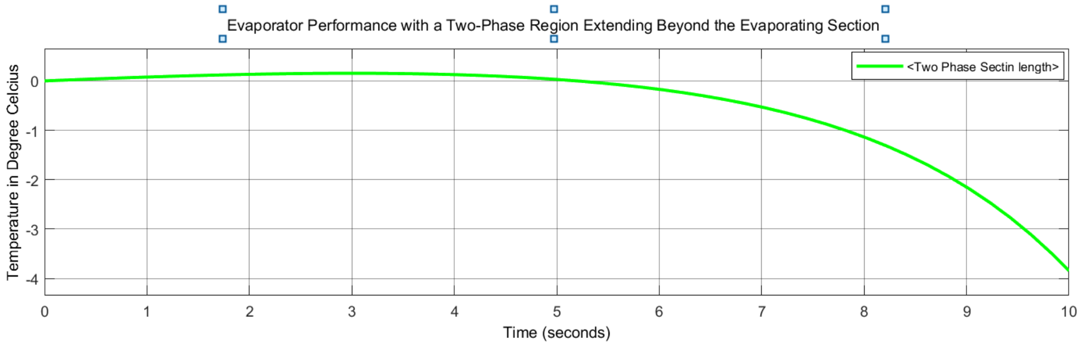


Figure 5.7: Two Phase Section Under Two-Phase Region Extending Beyond the Evaporating Section

5.4.2 Verifying of Evaporator Performance with a Two-Phase Region Extending Beyond the Evaporating Section

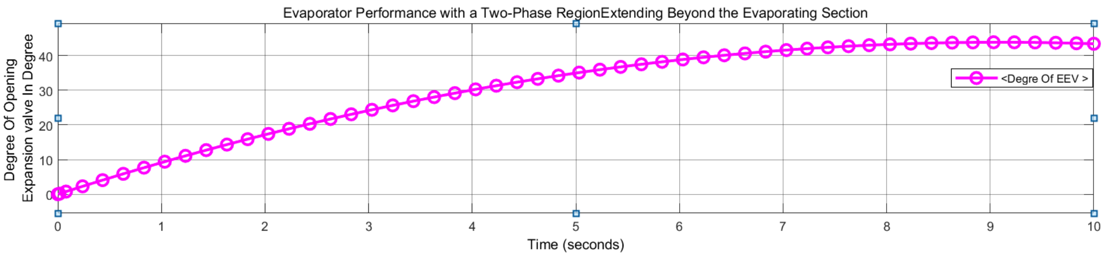


Figure 5.5: Degree of Opening Electronic Expansion Valve Under Two-Phase Region Extending Beyond the Evaporating Section

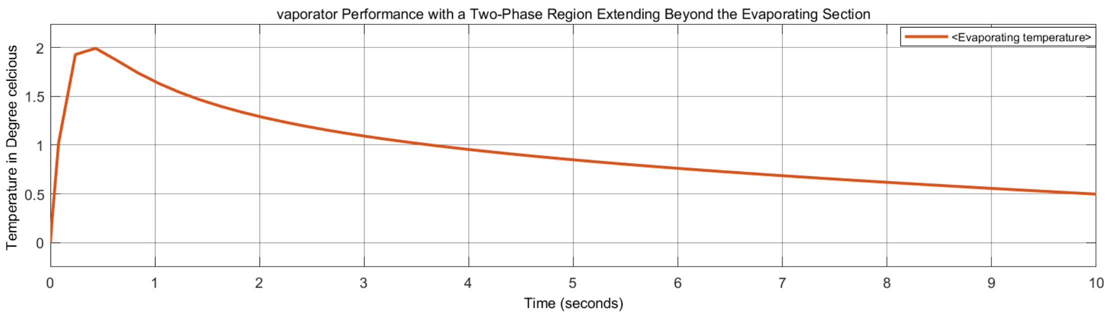


Figure 5.6: Evaporating Temperature Under Two-Phase Region Extending Beyond the Evaporating Section

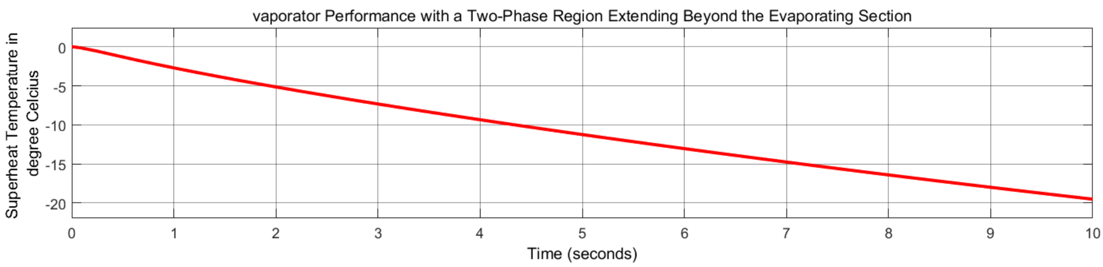


Figure 5.8: Superheat Temperature Under Two-Phase Region Extending Beyond the Evaporating Section

As demonstrated in Figure 5.4,5 and 6, when the electronic expansion valve opening increases and the length of the two-phase section extends beyond the evaporation section, the superheat at the evaporator outlet falls below zero. This presents a major issue for HVAC system performance, impacting both efficiency and components such as the compressor, as previously mentioned.
Moreover, a superheat level below zero can lead to even higher energy consumption, as the system must exert more effort to maintain the desired cooling effect.

5.5 Evaluating Evaporator Performance Under Superheat Temperature Overshoot Conditions

Superheat temperature overshoot in the evaporator of an HVAC system can occur due to several factors, which affect the system's efficiency and performance. Superheat temperature is the refrigerant vapor temperature above its boiling point, and it plays a critical role in effective heat absorption within the evaporator.

A major factor contributing to superheat overshoot is the expansion valve opening. If the valve is too closed, refrigerant flow decreases, which can lead to higher superheat temperatures due to insufficient vaporization. To evaluate the system, let's consider that the expansion valve was manually reduced to 25%, 50%, and 75% of the expected normal opening to observe their effects on superheat temperature,with the return room temperature gradually increasing

5.5.1 Performance Analysis of an Evaporator with a 25% Reduction in the Opening Degree of an Electronic Expansion Valve

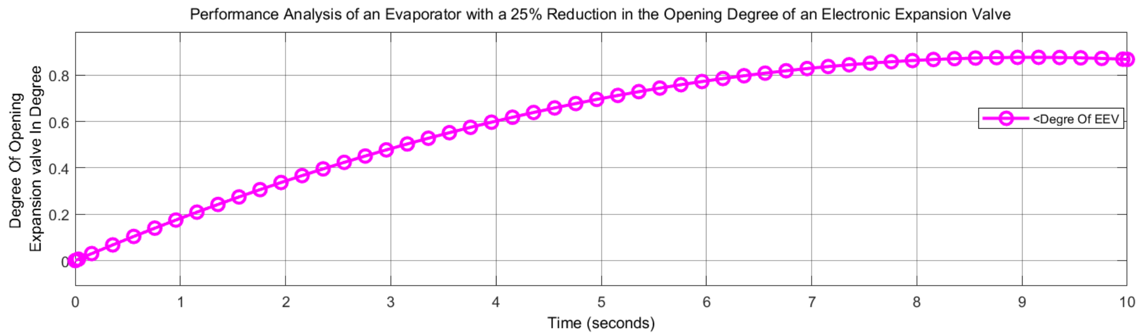


Figure 5.9: A 25% Reduction in the Opening Degree of an Electronic Expansion Valve

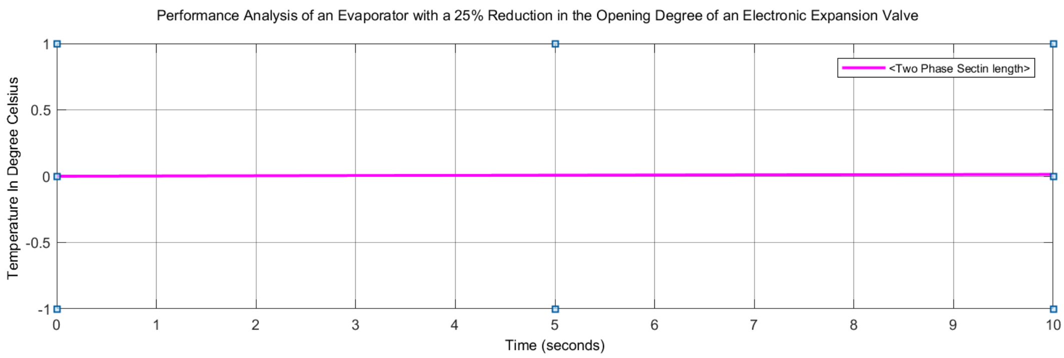


Figure 5.10: Two Phase Section Area with a 25% Reduction in the Opening Two Phase Section Area

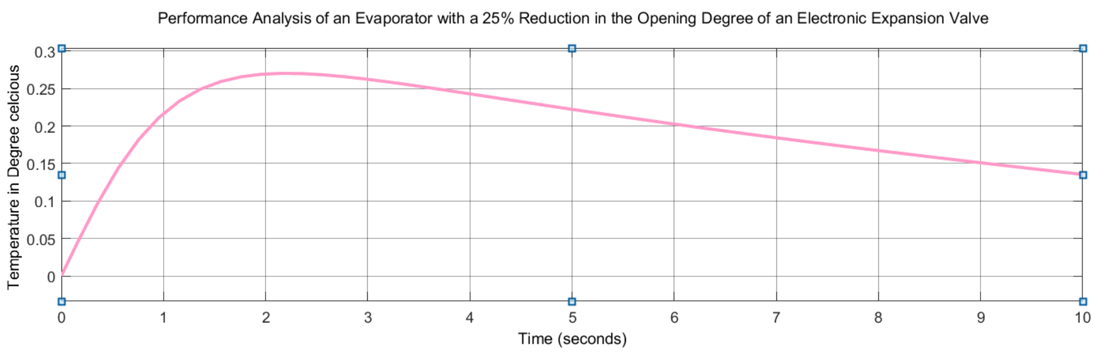


Figure 5.11: Evapoarting Rate Temperature with 25% Reduction of Degree of Opening Electronic Expansion Valve

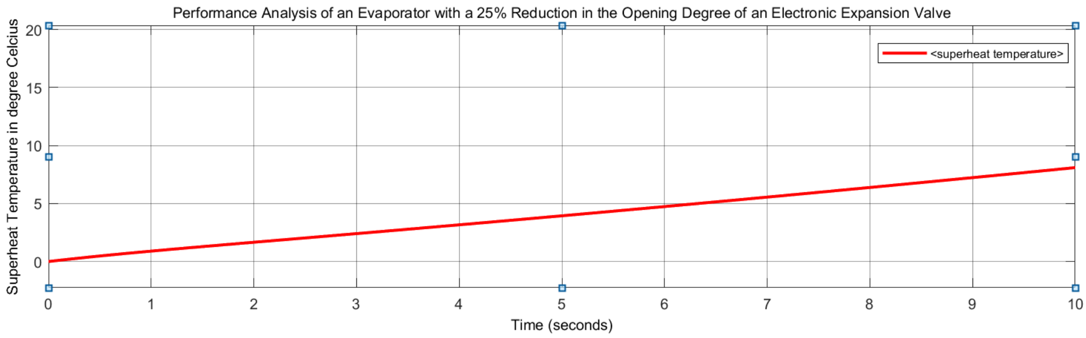


Figure 5.12: Superheat Temperature with 25% Reduction in the Opening Degree of an Electronic Expansion Valve

As shown in Figs. 5.8, 5.9, 5.10, and 5.11, this simulation examines the impact of reducing the electronic expansion valve opening by 25% from its normal setting. This results in a sharp increase in the superheat temperature at the evaporator outlet, leading to a significant reduction in the heat exchange rate, especially in the two-phase section near the zero-length point. The effect is further exacerbated by a gradual rise in ambient room temperature. These findings highlight the complex relationship between the expansion valve setting, superheat temperature, heat exchange rate, and ambient temperature. It is important to note that other factors, such as the condensation process, compressor efficiency, evaporator size, and refrigerant quality, can also affect the superheat temperature at the evaporator outlet. To optimize system performance, these factors, along with the expansion valve setting, should be carefully consideredrameters may be required

5.5.2 Performance Analysis of an Evaporator with a 50% Reduction in the Opening Degree of an Electronic Expansion Valve

Let's investigate the effects of reducing the electronic expansion valve to 50% of its normal opening. This significant decrease can have various impacts on system performance

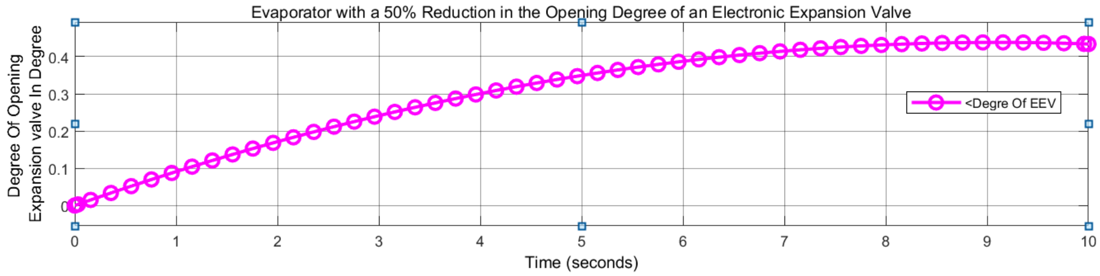


Figure 5.13: 50% Reduction Opening Degree Of Electronic Expansion Valve

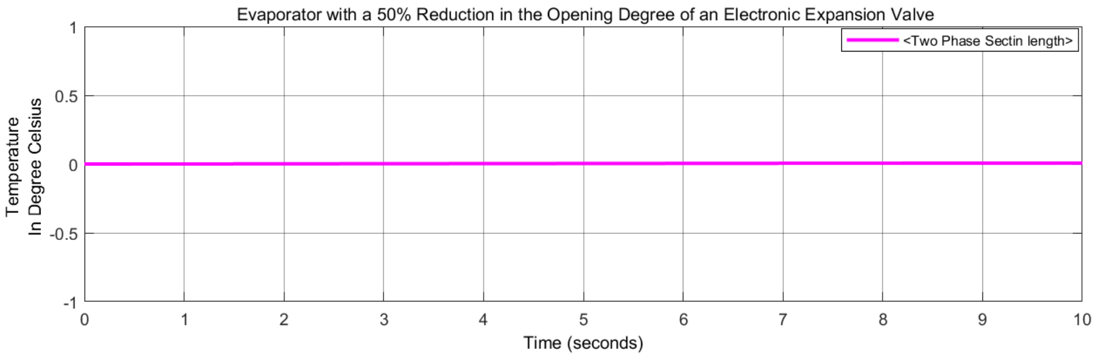


Figure 5.14: Two Phase Section Area with 50% Reduction Opening Degree Of Electronic Expansion Valve

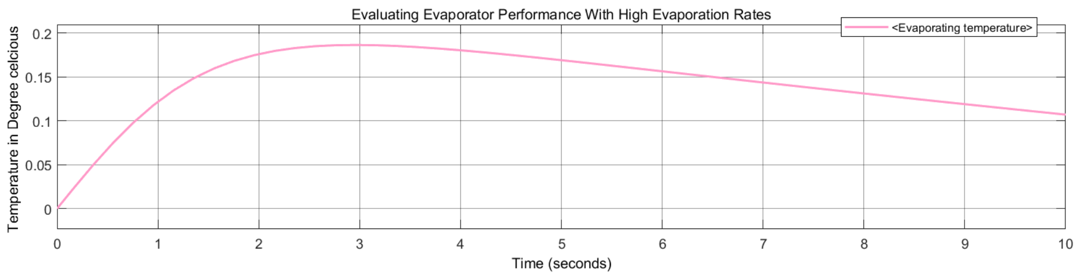


Figure 5.15: Evaporating Rate with 50% Reduction Opening Degree Of Electronic Expansion Valve

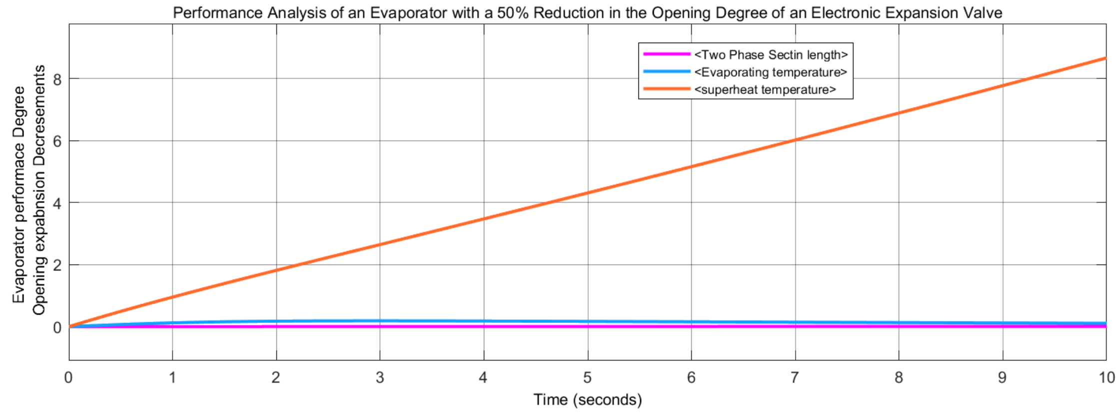


Figure 5.16: Two Phase section with 50% Reduction Opening Degree Of Electronic Expansion Valve

As shown in Figs. 5.12, 5.13, 5.14, and 5.15, further reducing the expansion valve opening by 50% leads to a more significant increase in superheat temperature at the evaporator outlet. This results in a further substantial decrease in the heat exchange rate, particularly in the two-phase section near the zero-length point. This indicates reduced system efficiency, leading to higher energy consumption and a shorter component lifespan. The effect is further aggravated by the gradual rise in ambient room temperature. These findings highlight the importance of properly balancing system parameters to ensure efficient operation and prolong the life of system components

5.5.3 Performance Analysis of an Evaporator with a 75 % Reduction in the Opening Degree of an Electronic Expansion Valve

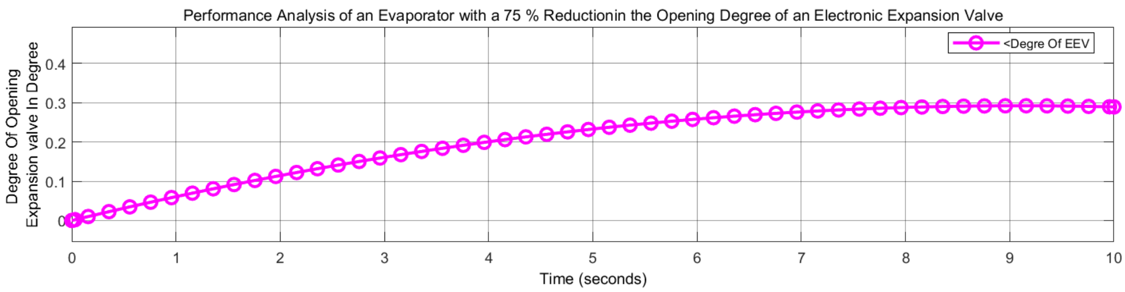


Figure 5.17: When 75% Reduction in the Opening Degree of an Electronic Expansion Valve

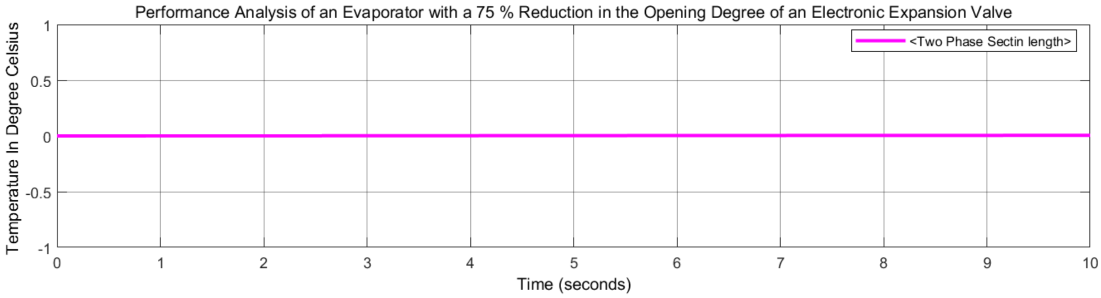


Figure 5.18: Two Phase Section Area Under 75% Reduction in the Opening Degree of an Electronic Expansion Valve

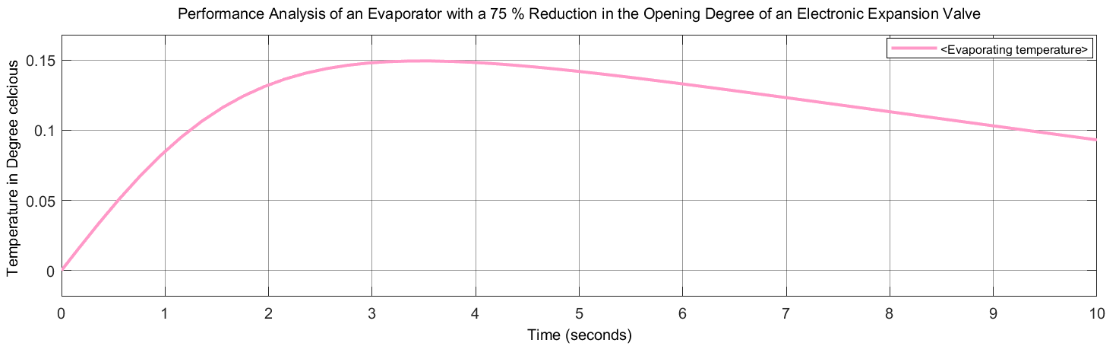


Figure 5.19: Evaporating Temperature Under 75% Reduction in the Opening Degree of an Electronic Expansion Valve

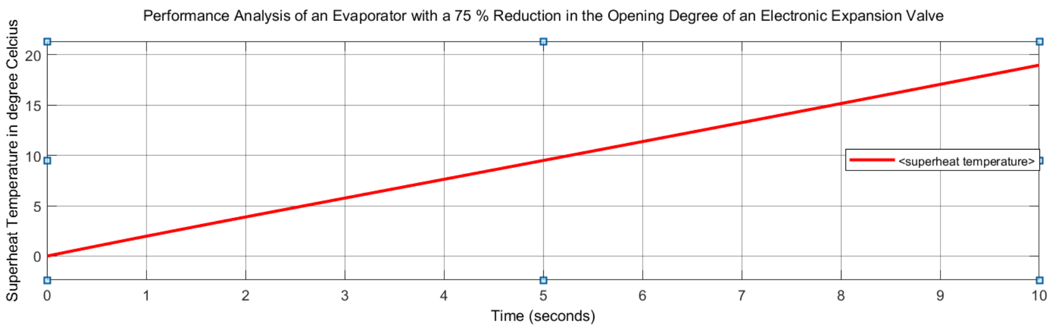


Figure 5.20: Superheat Temperature Under 75% Reduction in the Opening Degree of an Electronic Expansion Valve

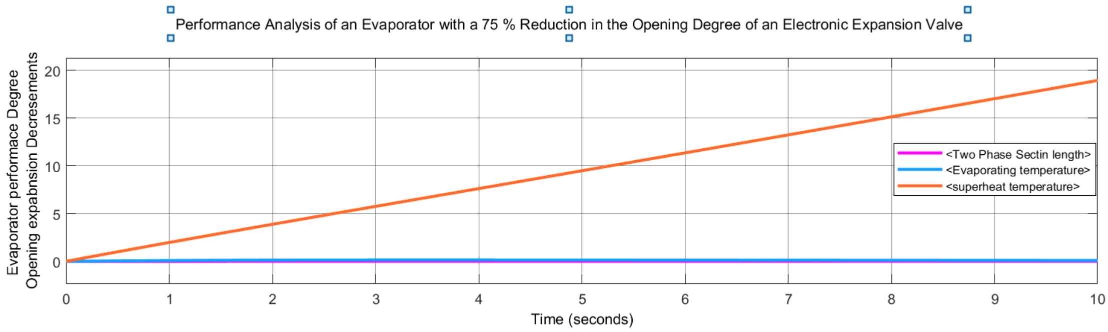


Figure 5.21: Evaporator Performance Analysis Under 75% Reduction in the Opening Degree of an Electronic Expansion Valve

As shown in Figures 5.16 and 5.19, when the degree of the electronic expansion valve is reduced by 75% from its normal opening setting, the evaporator outlet experiences overshoot. The simulation results indicate that as the degree of opening of the electronic expansion valve increases, the superheat temperature rises sharply, even with a constant return room temperature. This phenomenon occurs because the evaporating temperature decreases rapidly, causing the two-phase section of the system to approach zero. Therefore, it is confirmed that unregulated superheat temperature negatively impacts the efficiency and performance of the cooling system, as outlined in the problem statemen

5.6 Integral Terminal Sliding Mode with Automatic Gain Tuning Fuzzy Logic Controller for Regulating Evaporator Outlet Superheat Temperature

This paper presents a novel approach that combines Integral Terminal Sliding Mode Control (ITSMC) with an Automatic Tuning Fuzzy Logic Controller to regulate the evaporator outlet superheat temperature, even under significant fluctuations in return room temperature. By integrating ITSMC with automatic gain tuning, the system effectively manages superheat temperature, improving cooling efficiency and overall performance.

The method uses Integral Sliding Mode Control (ISMC) to address singularity issues in the evaporator dynamics. While Terminal Sliding Mode Control (TSMC) utilizes nonlinear switching manifolds for finite-time convergence, it does not always guarantee that error dynamics will reach zero within that time. ITSMC resolves this by adding an integral term to the sliding surfaces, ensuring that error dynamics converge to zero within a specified period.

In summary, this approach significantly enhances the reliability and responsiveness of temperature regulation in HVAC systems, particularly in environments with fluctuating thermal loads

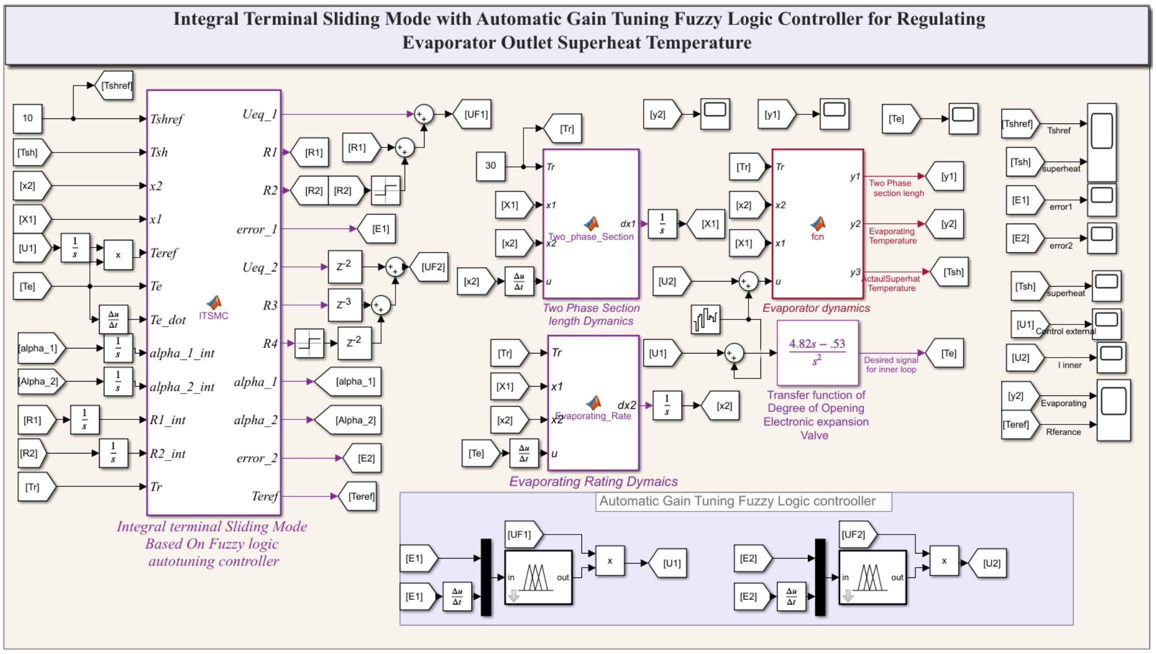


Figure 5.22: Designed Control Block Diagram of Integral Terminal Sliding Mode with Automatic Gain-Tuning Fuzzy Logic Controller

5.7 Integral Terminal sliding Mode Response Without Applying Automatic Gain Tuning Fuzzy logic Controller

A. Let's assume the room temperature remains constant at 27°C, while the desired superheat evaporator outlet temperature is set at 10°C. Note that this return room temperature exceeds the required superheat evaporator outlet temperature

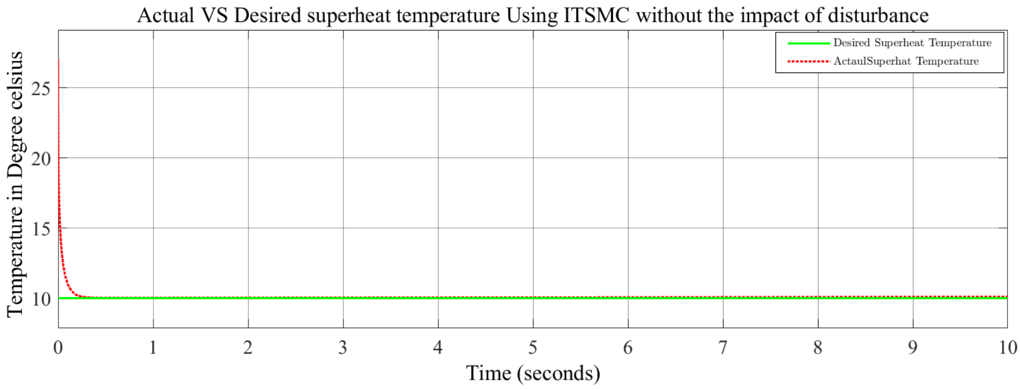


Figure 5.23: Desired vs Actual Superheat Temperature Using ITSMC Under Constant Return Room Temperature Conditions Without Disturbance Effects

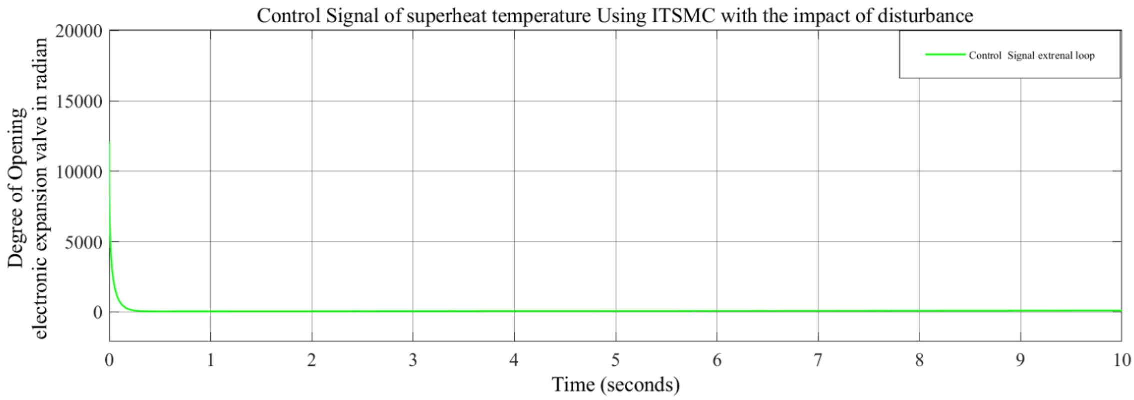


Figure 5.24: Control Signal for Superheat Temperature Using ITSMC with Constant Return Room Temperature and Without Effects Disturbance

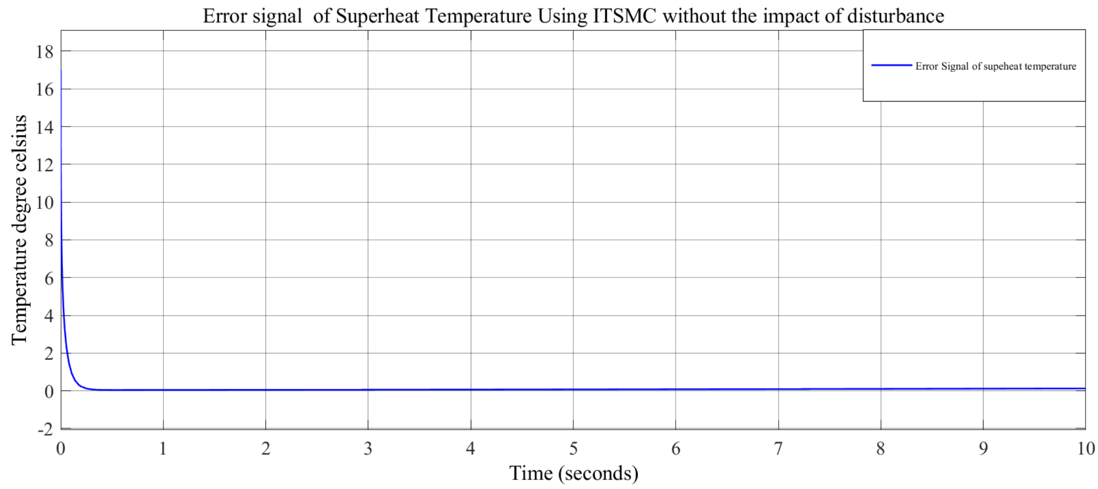


Figure 5.25: Error Signal Response for Superheat Temperature Using ITSMC Under Constant Return Air Conditions and in the Absence of Disturbance

B Let's assume the room temperature remains constant at 27°C, with external disturbances affecting the system. The desired superheat evaporator outlet temperature is set at 10°C. Note that this room temperature exceeds the required superheat evaporator outlet temperature

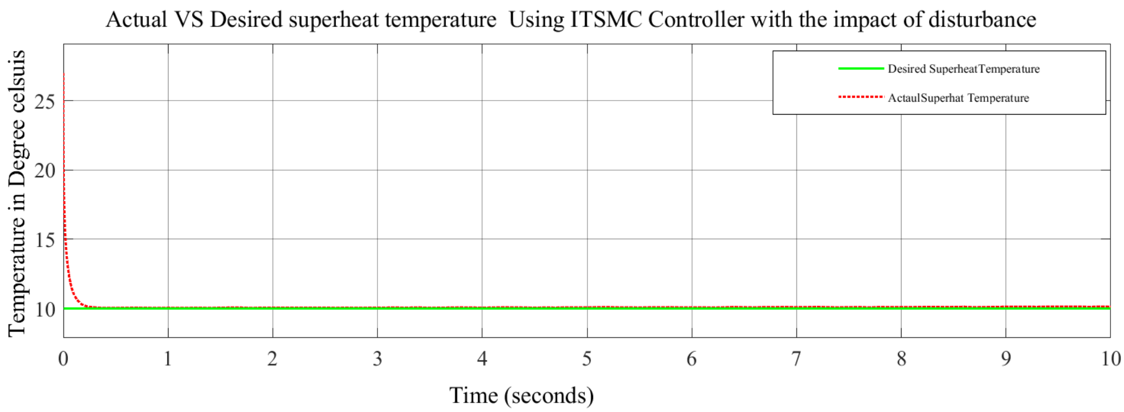


Figure 5.26: Desired Vs Actual Superheat Temperature Using ISMC Under Constant Conditions With Disturbance Effects

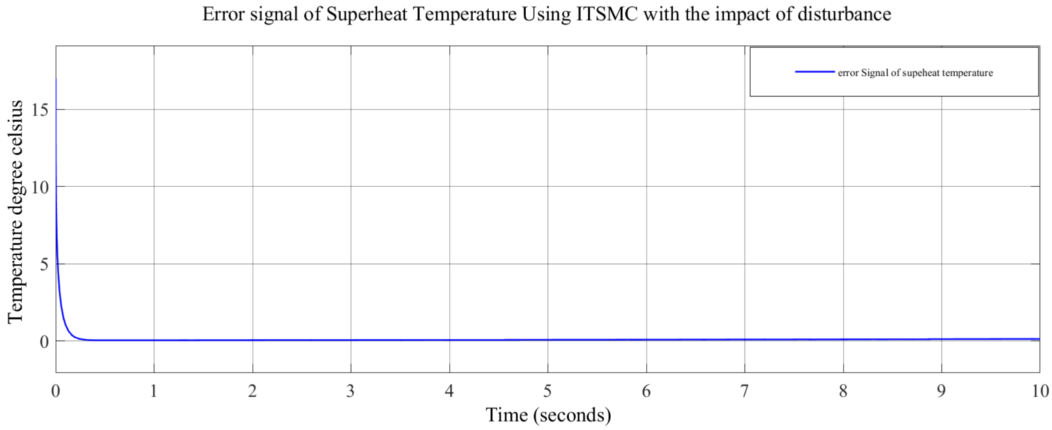
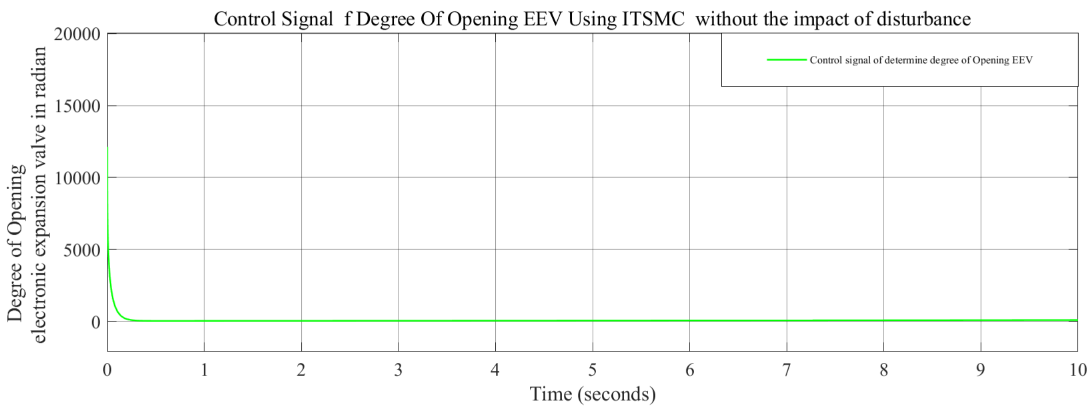


Figure 5.27: Error Signal Response for Superheat Temperature Using ITSMC Under Constant Conditions with Disturbance Effects



Control Signal of Superheat Temperature of Using ISMC Under Constant Conditions With Disturbance Effects

5.7.1 When Room Temperature Under Desired Temperature

- Let's assume the room temperature remains constant at 0°C, with external disturbances affecting the system. The desired superheat evaporator outlet temperature is set at 10°C. This scenario is used to demonstrate the effectiveness of the Integral Terminal Sliding Mode Controller (ITSMC) in achieving and maintaining the desired superheat evaporator outlet temperature.

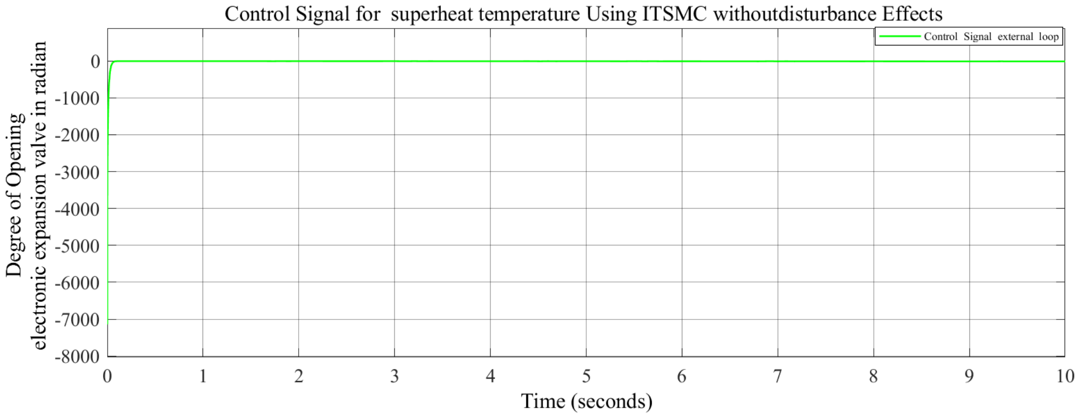


Figure 5.28: Control Signal for Superheat Temperature Using ISMC Under Constant Conditions Without Disturbance Effects

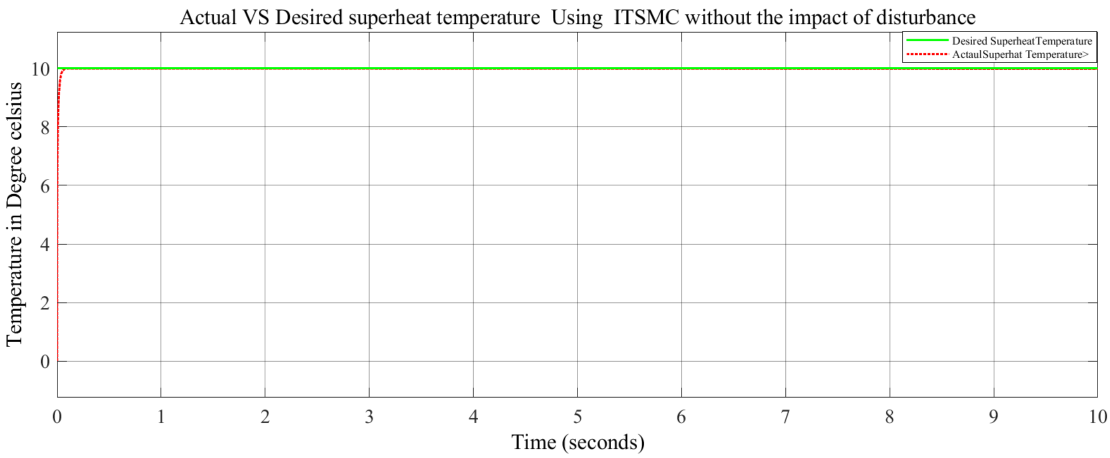


Figure 5.29: Actual And Desired Superheat Temperature Using ITSMC Under Constant Conditions Without Disturbance Effects

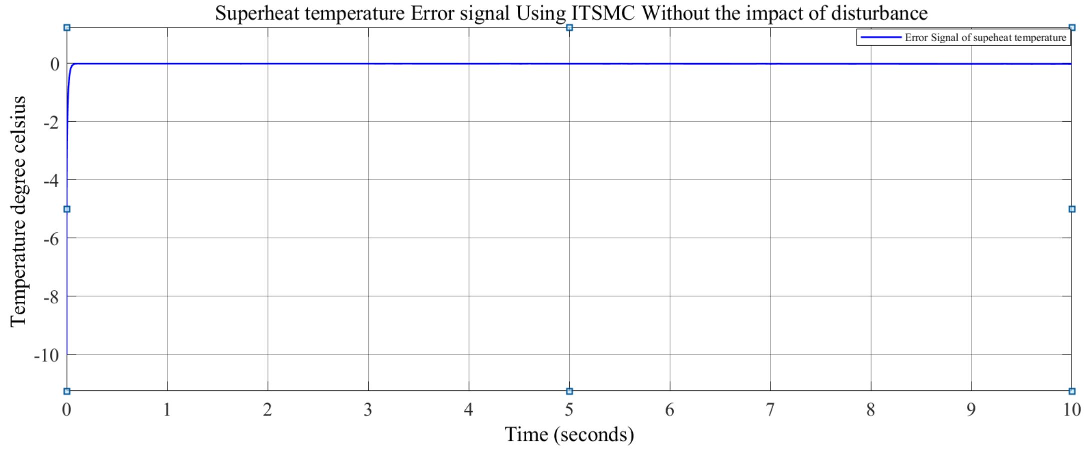


Figure 5.30: Error Signal Superheat of temperature Using ISMC Under Constant Conditions Without Disturbance Effects

5.7.2 Simulation Response Results Considering Stepwise Changes in Return Room Temperature

A. Let us assume that the room temperature changes in discrete steps without external disturbances affecting the system. The evaluation aims to demonstrate the effectiveness of the designed Integral Terminal Sliding Mode Controller (ITSMC) in achieving and stabilizing the desired temperature despite these stepwise variations

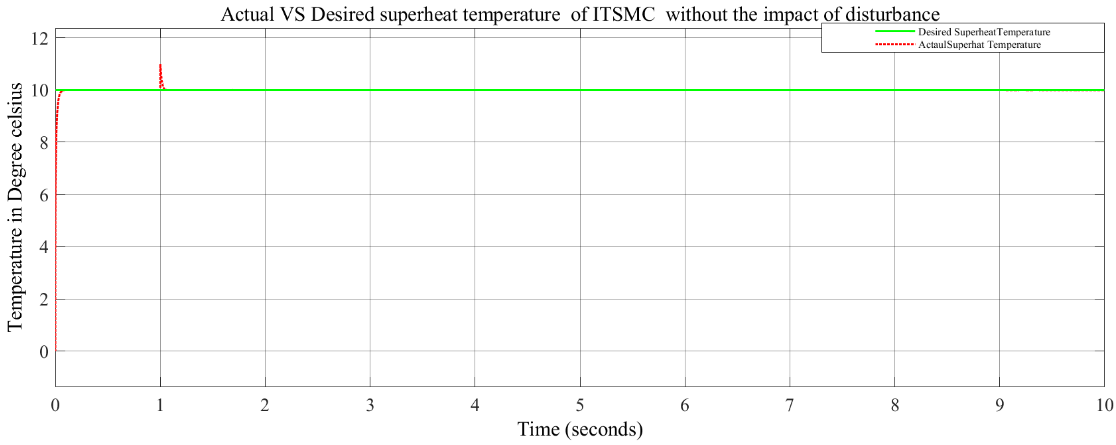


Figure 5.31: Actual vs Desired Superheat Temperatures Response to a Unit Step Input Without Disturbance Effects

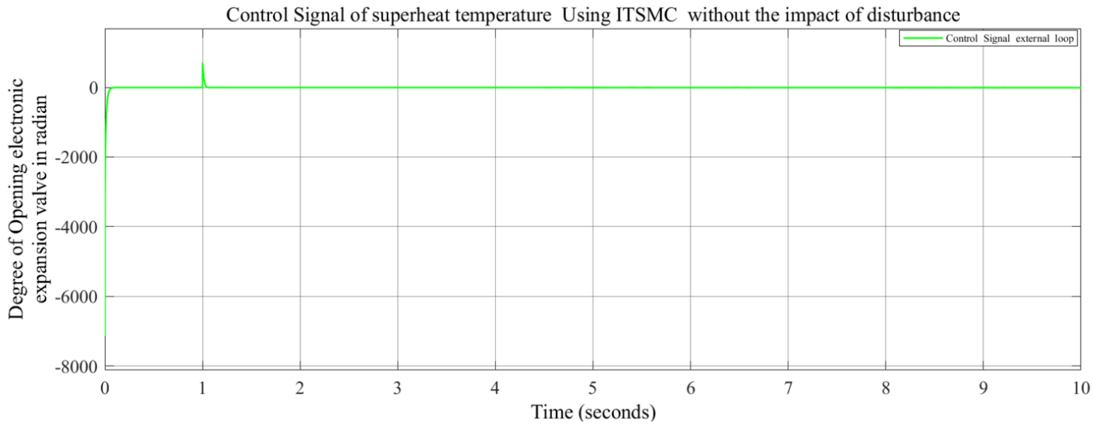


Figure 5.32: Control Signal Response Result of Superheat Temperatures Response Under Unit step Input without Effects of Disturbance

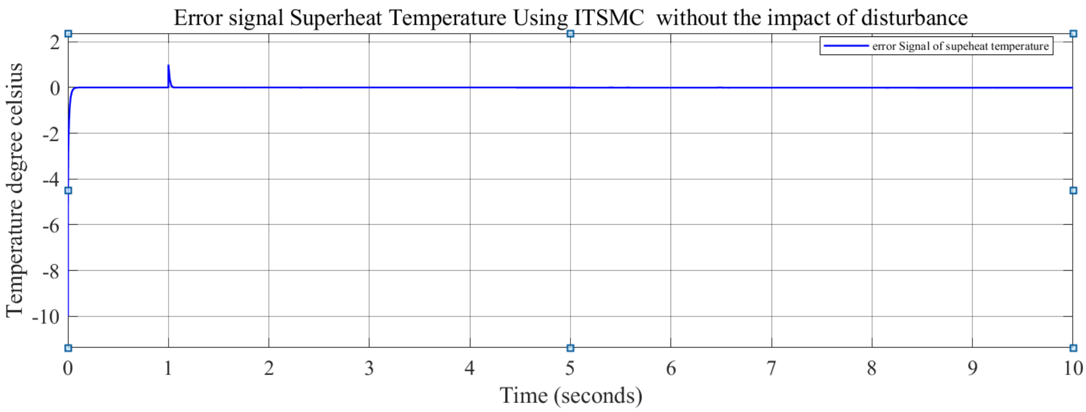


Figure 5.33: Error Signal Response Result of Superheat Temperatures Response Under Unit step Input without Effects of Disturbance

B. Let's assume that the room temperature experiences discrete step changes with external disturbances affecting the system. The objective of the evaluation is to demonstrate how effectively the designed Integral Terminal Sliding Mode Controller (ITSMC) can maintain the desired temperature despite these stepwise variations.

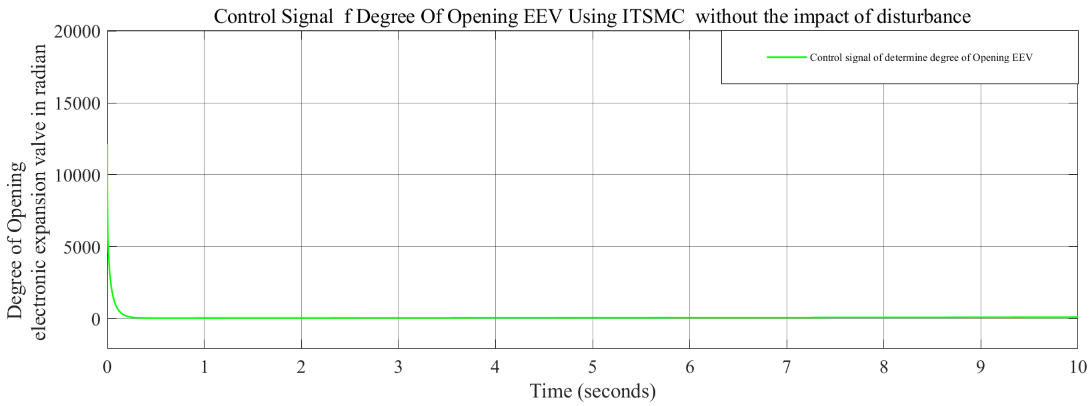


Figure 5.34: Actual and Desired Of Superheat Temperature Response under Step Input With Effects Disturbance

Figure 5.35: Control Signal Of Superheat Temperature under Step Input With Effects Disturbance

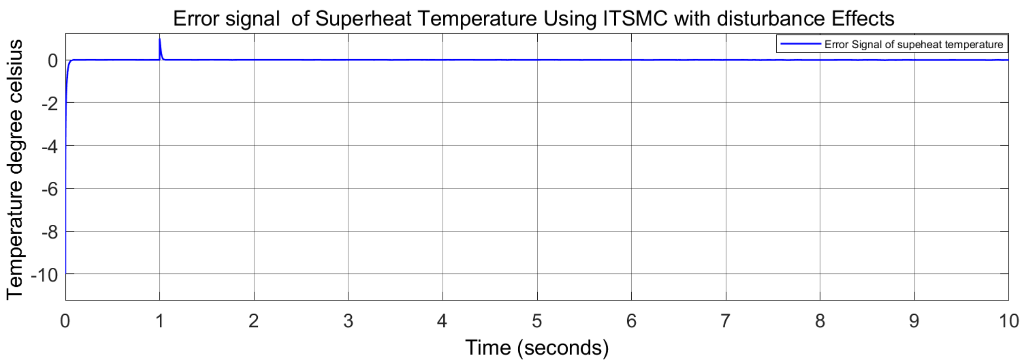


Figure 5.36: Error Signal Of Superheat Temperature under Step Input With Effects Disturbance

5.7.3 Simulation Response Results Considering the High Dynamics of Room Temperature Variations, Excluding the Effects of Disturbance

- Let's examine the room temperature variation dynamics as shown in the graph below to evaluate the effectiveness of the ITSMC (Integral Sliding Mode Control) approach without extrenal Distrurbance

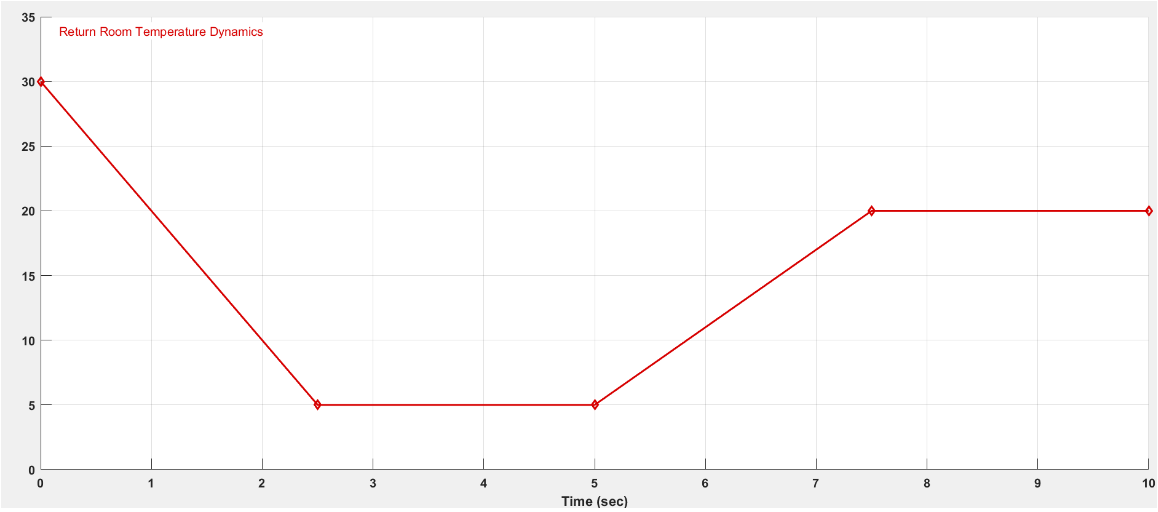


Figure 5.37: Considering the Dynamic Variations in Return Room Temperature for the Evaporator Coils

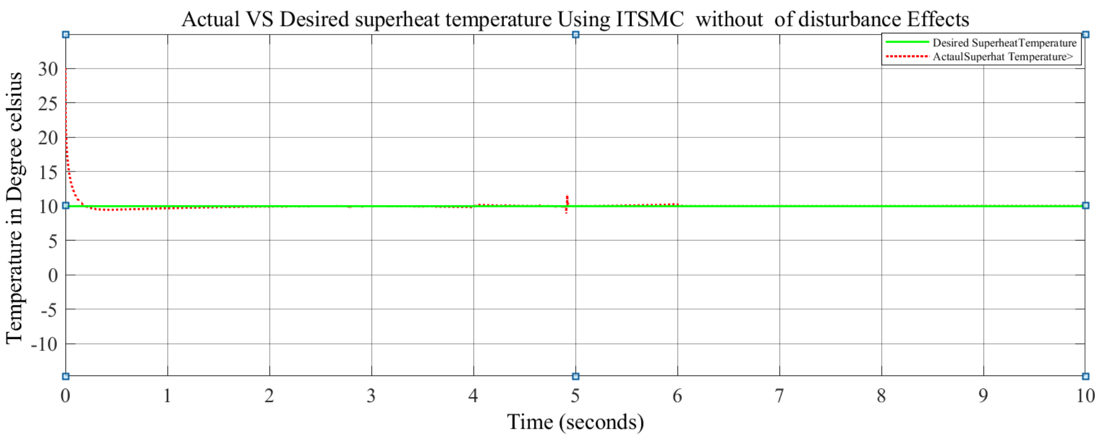


Figure 5.38: Simulation Response Results for Actual vs Desired Superheat Temperature Considering Highly Dynamic Variations in Return Room Temperature

5.7.4 Simulation Response considering highly Variation of Return Room temperatre With Effects of Disturbance

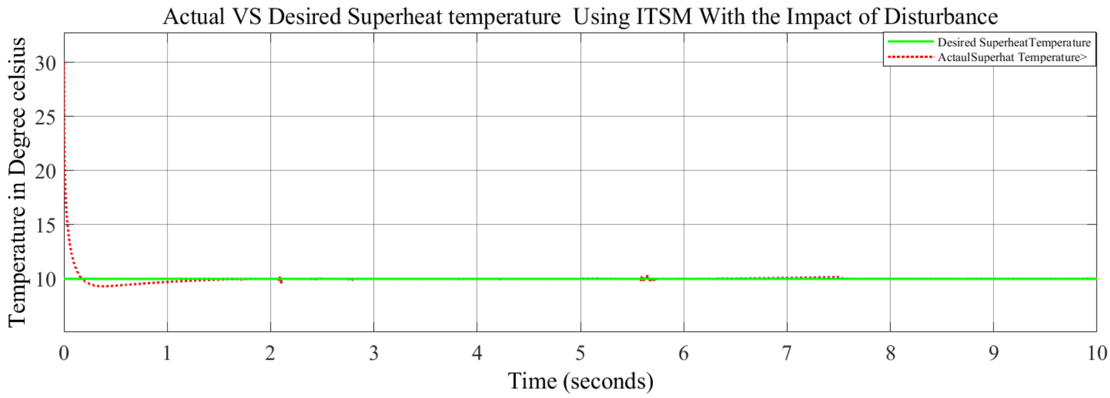


Figure 5.39: Simulation Response Results of Actual vs Desired Superheat Temperature Using ITSMC, Accounting for the Effects of Disturbance

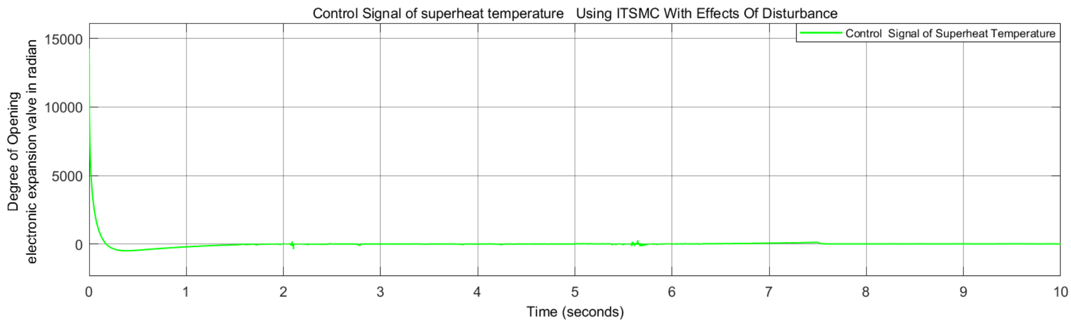


Figure 5.40: Simulation Response Results for Control Signal of Superheat Temperature Using ITSMC, Accounting for the Effects of Disturbance

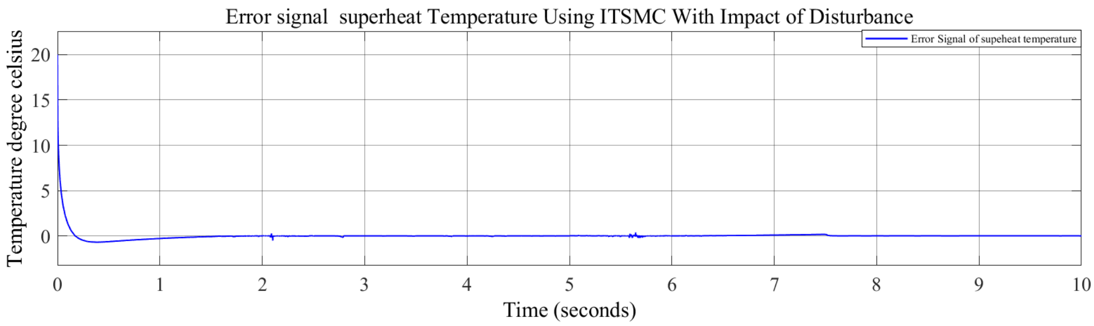


Figure 5.41: S Simulation Response Results for Error Signal of Superheat Temperature Using ITSMC, Accounting for the Effects of Disturbance

5.8 Simulation Results Using an Integral Terminal Sliding Mode Controller with Automatic Fuzzy Logic Gain Tuning

A, Let us assume a constant room temperature of 30°C and a target evaporator outlet temperature of 10°C. This setup aims to demonstrate how effectively the designed Integral Terminal Sliding Mode (ITSM) controller, enhanced with Auto Gain Tuning and Fuzzy Logic, can achieve and maintain the desired temperature.

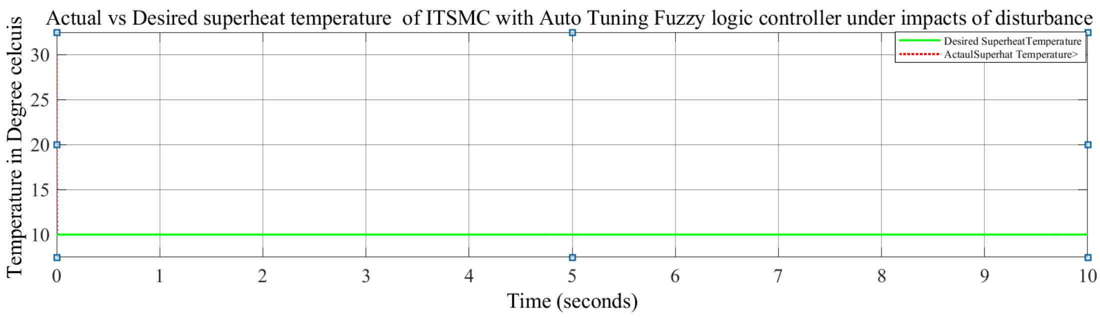


Figure 5.42: Simulation Response of Actual vs. Desired Superheat Temperature Using ITSMC with Auto-Tuning FLC Under Disturbance Effects

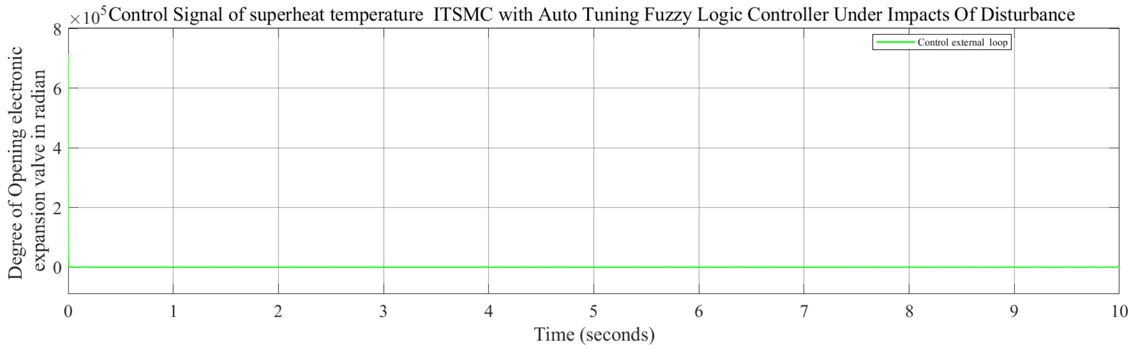


Figure 5.43: Simulation Result Response of Control signal Superheat Temperature Using ITSMC With Auto Tuning FLC with effects of Disturbance

1

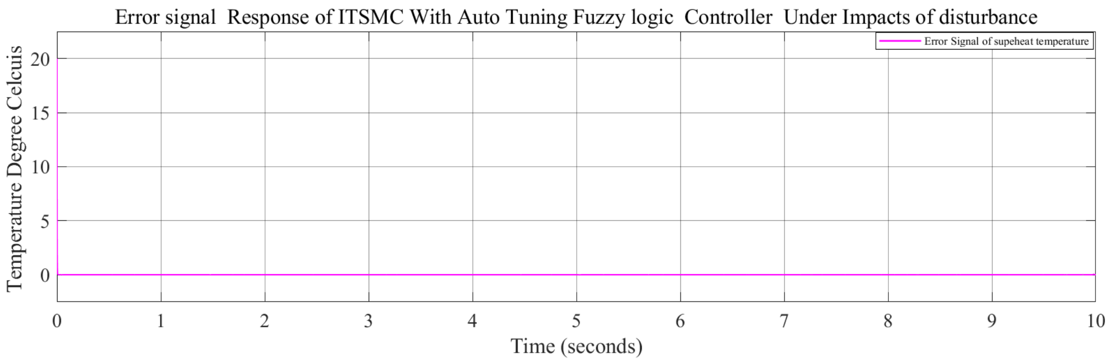


Figure 5.44: Simulation Response of Error Signal Using ITSMC with Auto-Tuning FLC Under Disturbance Effects

B. Let's consider a scenario where the return room temperature varies stepwise, while the target room temperature is set at 10°C. This setup illustrates how the designed Integral Terminal Sliding Mode (ITSM) controller effective , combined with Auto Gain Tuning and Fuzzy Logic, can successfully achieve and maintain the desired temperature despite these variations

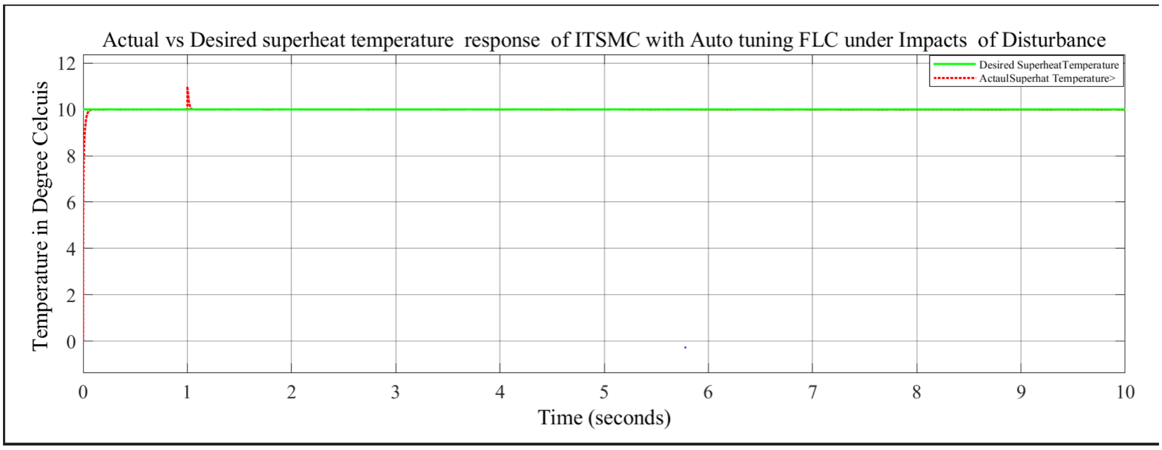


Figure 5.45: Simulation Response Results of Actual vs Desiredd Superheat Temperature Using ITSMC With Auto Tuning FLC with effects of Disturbance

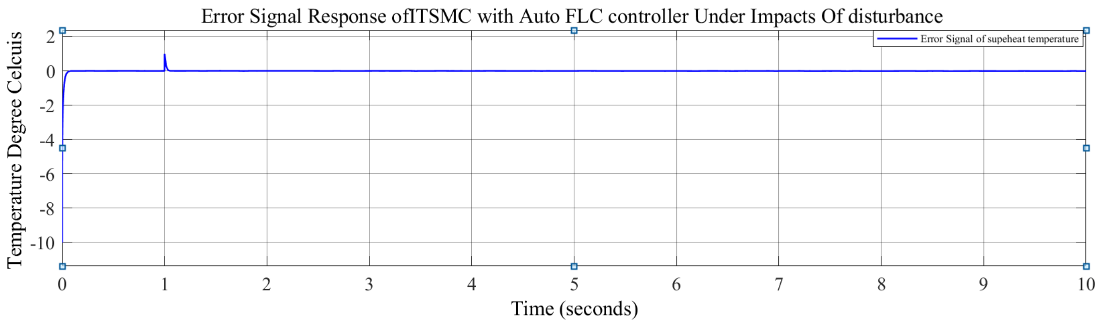


Figure 5.46: Simulation Response of error signal of Superheat Temperature Using ITSMC With Auto Tuning FLC with effects of Disturbance

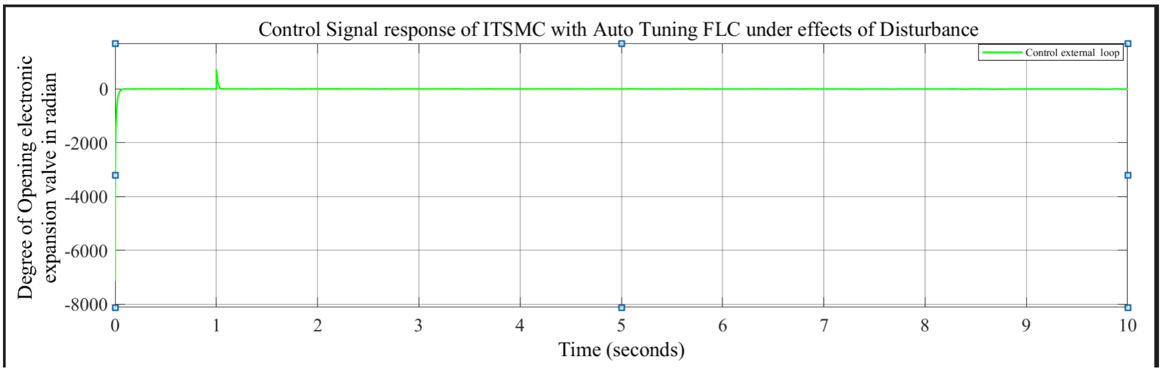


Figure 5.47: Simulation Response of Control signal Superheat Temperature Using ITSMC With Auto Tuning FLC with effects of Disturbance

5.9 Control signal simulation response results for high variations in return room temperature using an ITSMC with automatic gain tuning and a fuzzy logic controller

Let's assume there is significant variation in the room temperature. Meanwhile, the desired superheat temperature at the evaporator outlet is set to 10°C.

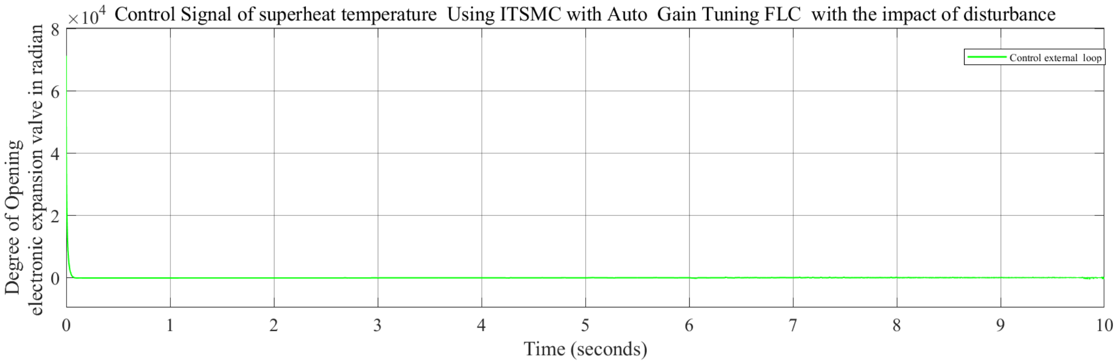


Figure 5.48: Control Signal Under Simulation response results under high variations in return room temperature using an ITSMC with auto-gain tuning and a fuzzy logic controller

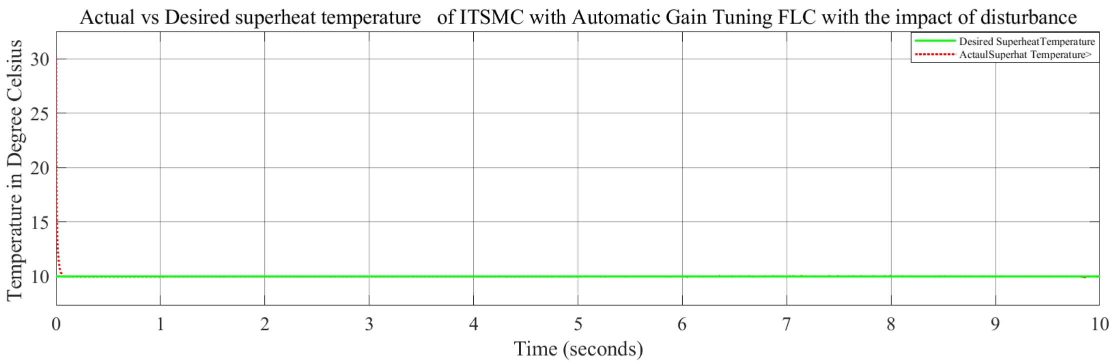


Figure 5.49: Actual vs Desired Superheat temperature Under Simulation response results under high variations in re- turn room temperature using an ITSMC with auto-gain tuning and a fuzzy logic controller

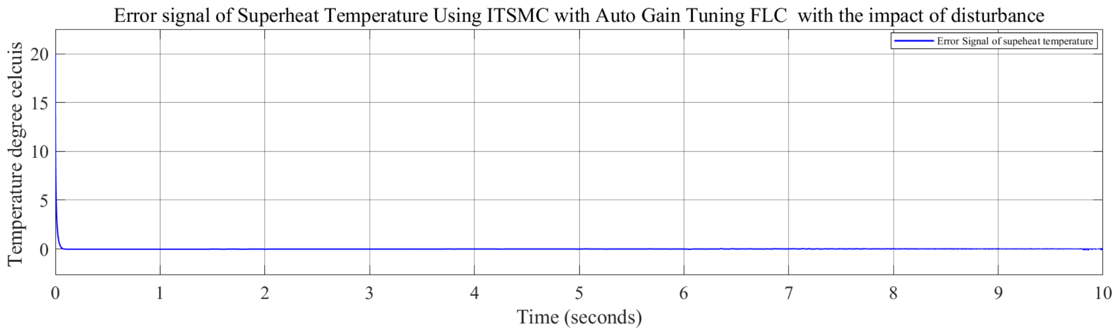


Figure 5.50: Error Signal Under Simulation response results under high variations in return room temperature using an ITSMC with auto-gain tuning and a fuzzy logic controller

5.10 Application Area

The proposed control strategy, which integrates Integral Terminal Sliding Mode Control (ITSMC) with Automatic Gain Tuning Fuzzy Logic Control (AGT-FLC), provides a sophisticated solution for managing a wide range of thermal processes in industrial plants. These applications include water cooling systems for data centers, immersion cooling for electronic equipment, chiller superheat control, industrial boilers, air blasting systems, batching plant cooling, and regulation of HVAC evaporator outlet temperatures, among others. The hybrid control approach demonstrates high effectiveness in regulating flow rates and optimizing performance across varying temperature dynamics, such as constant, step, and highly variable temperatures, as shown in Fig. 5.57. Simulation results confirm the controller's ability to handle all types of temperature fluctuations, even when return room temperatures experience unexpected shifts beyond gradual changes.

By combining ITSMC with AGT-FLC, the system dynamically adapts to changes in behavior, improving overall stability and efficiency in industrial operations. This integration reduces the need for human intervention, streamlining processes and minimizing the risk of errors. The robustness of ITSMC in handling disturbances and uncertainties, along with the adaptive tuning capabilities of AGT-FLC, ensures precise control in complex and dynamic environments. Ultimately, this approach enhances the performance of industrial systems while also reducing energy consumption and operational costs across a range of applications.

5.11 Discussion

The simulation results show that combining the Integral Terminal Sliding Mode Controller (ITSMC) with the Automatic Gain Tuning Fuzzy Logic Controller (AGT-FLC) is effective in controlling the superheat temperature at the evaporator outlet. This combined control strategy adjusts the electronic expansion valve to manage refrigerant flow rates, even with changing room temperatures and poor rack configurations, while also handling uncertainties and outside disturbances. The method ensures that the desired superheat temperature is maintained under different conditions, including dynamic and less-than-ideal situations.

The ITSMC is especially good at managing the non-linear behavior of the refrigerant flow, keeping the superheat temperature stable at the target level. The AGT-FLC helps minimize unwanted fluctuations and reduces both overshooting and undershooting, allowing for precise and timely adjustments in a two-loop control system. Key advantages of this approach include improved performance thanks to automatic tuning of control settings, and stable operation without chattering, made possible by the ITSMC design.

This paper presents a combined control strategy using ITSMC for HVAC systems. Its goal is not only to regulate the evaporator's superheat temperature but also to improve energy efficiency. The simulation results show that the proposed method achieves the desired superheat temperature in under 10 seconds, quickly reaching stable conditions for refrigerant flow and mass flow rates.

Chapter 6

Conclusion and Recommendation

6.1 Conclusion

This thesis provides a thorough exploration of the history of HVAC systems.It delves into the mathematical modeling of thermodynamics within the evaporator,focusing specifically on superheat temperature, evaporating temperature,and the dynamics of the two-phase section length. The differential equations are derived by combining energy and mass conservation principles with energy transfer theories.

The main contributions of this thesis can be summarized as follows:

- Development of a mathematical model for evaporator dynamics based on the integration of mass and energy conservation laws along with energy transfer theorems.
- Implementation of an Integral Terminal Sliding Mode Controller with Automatic Gain Tuning Fuzzy Logic to improve system performance.
- Design of the electronic expansion valve's degree of opening, along with the simulation and discussion of the resulting simulation outcomes
- Proving the global stability of the designed controller
- Simulate the above formulation **Matlab** and **simulink**

6.2 Recommandation ethiotelecom Data center

Ethio Telecom is advancing its energy efficiency by transitioning from traditional data center configurations to modular designs at select locations. However, the company still relies heavily on air conditioning for cooling, which consumes a significant amount of energy. Although air cooling systems can achieve desired Power Usage Effectiveness (PUE) levels and control the evaporator outlet temperature within a desired range, they remain energy-intensive.

To optimize power usage and reduce overall energy demands, Ethio Telecom should focus on evolving its data center strategies, particularly as 5G technology becomes increasingly integrated with cloud infrastructure. Continued reliance on air conditioning may hinder the company from meeting future PUE targets, especially as the demands of modern data centers increase. PUE is most effective in data centers that are designed to optimize rack usage, space, and energy efficiency.

Therefore, Ethio Telecom should consider transitioning to water cooling systems, which have been proven to be more energy-efficient and environmentally sustainable. By selecting data center sites that offer better access to water resources, such as the Gafarsa artificial lake and Tena Lakes, the company can reduce operational energy costs in the long term. While water cooling solutions may require a higher initial investment compared to air conditioning, they typically result in lower ongoing operational costs and contribute to significant energy savings over time.

In conclusion, adopting water cooling technology aligns with Ethio Telecom's commitment to improving energy efficiency and meeting the growing demands of future data centers. This strategic shift will help the company stay competitive in an era of rapidly evolving infrastructure and technology.

6.3 Future works

While this thesis has successfully met its primary objectives, there is substantial potential for further investigation and enhancement. The HVAC system studied in this research operates as a cascade with four main subsystems, where the output of one subsystem significantly affects the others. To refine the control system, future work should focus on developing a more sophisticated cascade control framework that incorporates both feedforward and feedback control strategies.

A key area for development is the application of a cascade feedback controller between the superheat temperature and the opening degree of the electronic expansion valve, as demonstrated in this study. Additionally, a feedforward controller could be introduced to link the superheat temperature to the compressor speed, allowing for dynamic adjustments to compressor speed based on varying operational conditions. This could improve energy efficiency by ensuring the compressor operates optimally in response to changes in system load.

Moreover, the system could benefit from a feedforward approach that connects the evaporator outlet superheat temperature to a variable-speed compressor. This would enable more precise control over the compressor's operation, further optimizing energy usage and cooling efficiency.

Additional improvements could involve determining the optimal running time for a constant-speed compressor and adjusting condenser fan speed using similar principles. Implementing a limit on the compressor's continuous operation time could help to further optimize energy consumption, reduce component wear, and extend the system's lifespan.

By integrating both feedforward and feedback control strategies, the robustness and cooling efficiency of the HVAC system could be significantly enhanced. This dual-control approach would enable the system to maintain optimal performance across a range of operating conditions, leading to improved energy efficiency and system reliability in future applications

Bibliography

[1] Wikipedia contributors. (n.d.). Data center. Wikipedia. Data center. *https://en.wikipedia.org/wiki/Data center*, 10:1–30, December 4, 2024,.

[2] Establishment of ethio telecom. Brief historical review of telecom sector in ethiopia. *https://www.ethiotelecom.et/history/*, 5:1–10, February 21, 2020.

[3] Chayan Nadjahi, Hasna Louahlia, and Stéphane Lemasson. A review of thermal management and innovative cooling strategies for data center. *Sustainable Computing: Informatics and Systems*, 19:14–28, 2018.

[4] Huhui Tian, Jiangang Lu, and Qinmin Yang. A self-tuning fuzzy logic controller for superheat of evaporator by using electronic expansion valve. In *2013 Sixth International Symposium on Computational Intelligence and Design*, volume 1, pages 277–280. IEEE, 2013.

[5] Kaveh Kianfar, Roozbeh Izadi-Zamanabadi, and Mehrdad Saif. Achievable optimal superheat temperature control in evaporators of hvac systems. In *2017 IEEE Conference on Control Technology and Applications (CCTA)*, pages 2008–2014. IEEE, 2017.

[6] Saber Abrazeh, Saeid-Reza Mohseni, Meisam Jahanshahi Zeitouni, Ahmad Parvaresh, Arman Fathollahi, Meysam Gheisarnejad, and Mohammad-Hassan Khooban. Virtual hardware-in-the-loop fmu co-simulation based digital twins for heating, ventilation, and air-conditioning (hvac) systems. *IEEE Transactions on Emerging Topics in Computational Intelligence*, 7(1):65–75, 2022.

[7] Xiaohong Yin, Xinli Wang, Ximei Liu, Ronghu Chi, Mingming Lin, and Yanni Wang. An iterative learning model predictive control strategy for evaporator. In *2018 37th Chinese Control Conference (CCC)*, pages 3652–3656. IEEE, 2018.

[8] Xudong Ding, Jing Wang, Peiyong Duan, Chenjie Yin, and Fan Zhang. A novel online auto-tuning pi controller for the superheat of evaporator with electronic expansion valve. In *2017 Chinese Automation Congress (CAC)*, pages 7513–7517. IEEE, 2017.

[9] Georgios Lymperopoulos and Petros Ioannou. Building temperature regulation in a multi-zone hvac system using distributed adaptive control. *Energy and Buildings*, 215:109825, 2020.

[10] ZiLong Li and Tianyu Zhang. Design of cascade feed-forward control system based on exothermic reactor. In *International Conference on Intelligent Manufacturing and Industrial Automation (CIMIA 2022)*, volume 12289, pages 17–21. SPIE, 2022.

[11] Zaiying Wang and Fang Luo. Control system design of evaporator based on pcs7 and smpt-1000. In *2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, pages 1723–1727. IEEE, 2018.

[12] Xudong Ding, Wenjian Cai, Lei Jia, and Changyun Wen. Evaporator modeling–a hybrid approach. *Applied Energy*, 86(1):81–88, 2009.

[13] https://mirai-intex.com/blog/the-evaporator-in-a-refrigeration system. The evaporator in a refrigeration system. *Applied Energy*, 86(1):1–5, April 26, 2024.

[14] Kaveh Kianfar, Mehrdad Saif, and Roozbeh Izadi-Zamanabadi. Adaptive super twisting sliding mode control of a hvac system. In *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 3520–3525. IEEE, 2014.

[15] Tahira Naseem, Abbas Javed, Mirza Tariq Hamayun, Muhammad Jawad, Ejaz A Ansari, Muhammad AB Fayyaz, Ali R Ansari, and Raheel Nawaz. Design of an energyplus model-based smart controller for maintaining thermal comfortable environment in non-domestic building. *IEEE Access*, 11:33134–33147, 2023.

[16] Qiulin Wang, Tailu Li, Yanan Jia, and Weiming Zhang. Thermodynamic performance comparison of series and parallel two-stage evaporation vapor compression refrigeration cycle. *Energy Reports*, 7:1616–1626, 2021.

[17] Arjan J van der Schaft. *Nonlinear state space H control theory*. Springer, 1993.

[18] Xinghuo Yu, Yong Feng, and Zhihong Man. Terminal sliding mode control–an overview. *IEEE Open Journal of the Industrial Electronics Society*, 2:36–52, 2020.

[19] Huawei Niu and Qixun Lan. Continuous integral terminal sliding mode control for a class of uncertain nonlinear systems. In *2018 37th Chinese Control Conference (CCC)*, pages 579–584. IEEE, 2018.

[20] Mario Sassano and Alessandro Astolfi. Dynamic lyapunov functions. *Automatica*, 49(4):1058–1067, 2013.

[21] Daniel E Wulbert. Nonlinear approximation with tangential characterization. *American Journal of Mathematics*, 93(3):718–730, 1971.

[22] Kihwan Eom, Kyungkwon Jung, and Harsha Sirisena. Performance improvement of backpropagation algorithm by automatic activation function gain tuning using fuzzy logic. *Neurocomputing*, 50:439–460, 2003.

Appendix A

Mathlab Algorithm for Superheat,evaporating and Two phase Section

```
Evaporator [y1,y2,y3] = fcn(Tr,x2,x1,u)
d=0.0081026;% inside diameter
A=0.00005156;%Cross Section area
h=1;%Refrigerant Enthalpy Difference
D=1300;%Refrigerant Density
y=0.93;%void mean fraction
q1=4;
q2=3;
xo=0.2;%Vapour quality
a1=-(d*pi*q1)/(D*h*(1-y)*A);
b1=(1-xo)/(D*(1-y));
z1=0.368;
z2=0.4005;
[z]=z2*x2+z1;
a2=(d*pi*q2)/(z*h);
c=1;
m=0.00173;
b2=xo/z;
L=11.5;
```

```
[y1]=a1*(Tr-x2)*x1+b1*u;% two phase lenth
[y2]=(-a2/z)*(Tr-x2)*x1+(b2/z)*u-m/z;%evaporating temperature
[y3]=(Tr-x2)*(1-exp(-c*(L-x1)/m));%superheat temperature
\\
Two_phase_Section(Tr,x1,x2,u)
d=0.0081026;% inside diameter
A=0.00005156;%Cross Section area
h=1;%Refrigerant Enthalpy Difference
D=1300;%Refrigerant Density
y=0.93;%void mean fraction
q1=0.4;
xo=0.2;%Vapour quality
a1=-(d*pi*q1)/(D*h*(1-y)*A);
b1=(1-xo)/(D*(1-y));
dx1=a1*(Tr-x2)*x1+b1*u;
```

Appendix B

Algorithm for Tuning Fuzzy Logic Controller

```
[System]
Name='A Fuzzy logic controler tunig algorithm'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=9
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='ErrorD'
Range=[-1 1]
NumMFs=3
MF1='N3':'trimf',[-3.667 -2 -0.3333]
MF2='Z3':'trimf',[-1.667 0 1.667]
MF3='PS3':'trimf',[0.3333 2 3.667]
```

```
[Input2]
Name='Error'
Range=[-1 1]
NumMFs=3
MF1='N3':'trimf',[-1.833 -1 -0.1666]
MF2='Z3':'trimf',[-0.8335 0 0.8335]
MF3='PS3':'trimf',[0.1666 1 1.833]

[Output1]
Name='tri'
Range=[0 10]
NumMFs=3
MF1='B3':'trimf',[-4.167 0 4.167]
MF2='Z3':'trimf',[0.8333 5 9.167]
MF3='S3':'trimf',[5.833 10 14.17]

[Rules]
1 1, 1 (1) : 1
1 2, 3 (1) : 1
1 3, 2 (1) : 1
2 1, 3 (1) : 1
2 2, 2 (1) : 1
2 3, 1 (1) : 1
3 1, 2 (1) : 1
3 2, 3 (1) : 1
3 3, 1 (1) : 1
```

Appendix C

Designed Control Algorithm

```
function [Ueq_1, R1, R2, error_1, Ueq_2, R3, R4, alpha_1, alpha_2, erro
    % Define constant parameters
    L = 11.5;
    lambda1 = 8;
    lambda2 = 4;
    xo = 0.02; % Refrigerant vapor quality
    Beta_1 = 10;
    Beta_2 = 1;
    Beta_3 = 4;
    Beta_4 = 10;
    z1 = 0.368;
    z2 = 0.4005;
    d = 0.0081026; % Inside diameter
    q2 = 0.5;
    h = 105.9;

    % Slopes for evenly distributed refrigeration
    Z = z2 * x2 + z1;
    a_2 = -((d * pi * q2) / h) / Z;
    b_2 = xo / Z;

    % Two-phase section length parameters
```

```
    A = 0.00005156; % Cross-sectional area
    D = 1300; % Refrigerant density
    y = 0.93; % Void mean fraction
    q1 = 0.4;
    a1 = -(d * pi * q1) / (D * h * (1 - y) * A);
    m = 0.00713;
  % Compute dx1 and dx2
    dx1 = a1 * (Tr - x2) * x1 + b1 * u;
    dx2 = (a_2 * (Tr - x2) * x1 + b_2 * u - m) / Z;

    % Error 1: Superheat temperature error
    error_1 = Tsh - Tshref;

    % Integral of error 1
    error_int1 = lambda1 * error_1;

    % Integral sliding surface 1
    S_1 = error_1 + lambda1 * error_int1;

    % Equivalent controller calculation 1

% Prevent division by zero by \\adding a small epsilon
    epsilon = 1e-6;
    Ueq_1 = (-alpha_2 + lambda1 * error_int1) / (alpha_1 + epsilon);
    Ueq_1_int = (-alpha_2_int +lambda1 * error_int1^2) / (alpha_1_int -

    % Control terms R1 and R2 for the first part
    R1 = Beta_1 * S_1 / (alpha_1 + epsilon);
    R2 = Beta_2 * S_1 / (alpha_1 + epsilon);

    % Integral control terms for R1 and R2
    R1_int = Beta_1 * error_int1 / (alpha_1_int + epsilon);
```

```
    R2_int = Beta_2 * error_int1 / (alpha_1_int + epsilon);

    % Overall external loop controller
    U1_int = Ueq_1_int + R1_int + R2_int;
    U1 = Ueq_1 + R1 + R2;

    % Define Teref_dot
    Teref = Te * U1_int;
    Teref_dot = Te_dot * U1_int + Te * U1;

    % Error 2: Temperature error
    error_2 = Te - Teref;

    % Integral of error 2
    error_int2 = lambda2 * error_2;

    % Integral sliding surface 2



    % Equivalent controller Sliding Mode (ISM)
    alpha_3 = b_2 / Z;
    alpha_4 = a_2 * x1 * dx2 + a_2 * (Tr - x2) * x1 - Teref_dot;

    % Prevent division by zero by adding a small epsilon
    Ueq_2 = (-alpha_4 - lambda2 * error_int2) / (alpha_3 + epsilon);

    % Control terms for the second part with ISM
    R3 = -Beta_3 * S_2 / (alpha_3 + epsilon);
    R4 = -Beta_4 * S_2 / (alpha_3 + epsilon);
end

\end
```