THE UNIVERSITY OF TEXAS AT TYLER

Temperature and Humidity control in an Evaporative Cooling based AC system for Residential Applications

Final Report– MENG 5330 Process Control

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Outline of report

Introduction

An evaporative cooler (EC) is a device that cools air through the evaporation of water using a heat and mass transfer process.

Evaporative cooling differs from vapor-compression based AC systems by

- Consuming less energy
- Being more environmentally friendly
- Optimal performance in hot and dry climate conditions[1]

This project will focus on a direct evaporative cooling AC system with a desiccant wheel for temperature and humidity control.

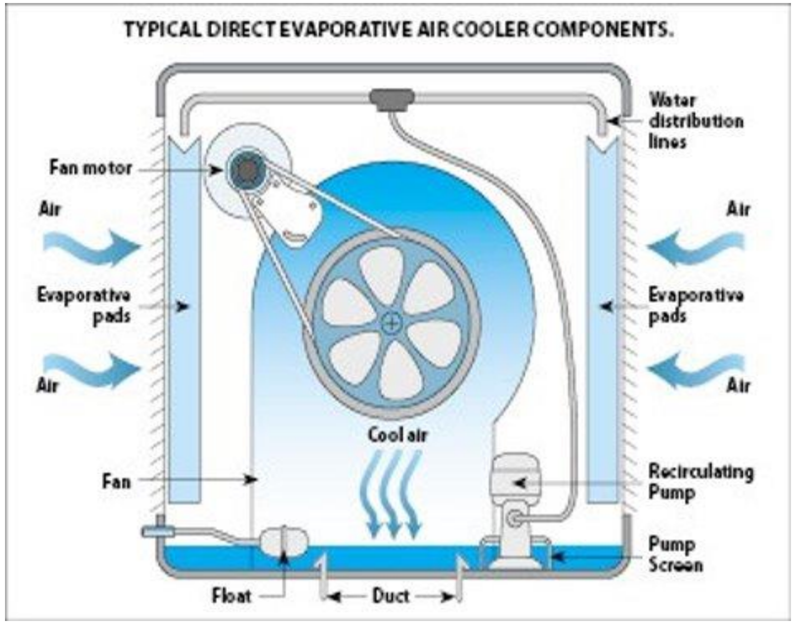


Fig 1. Operation of the Evaporative cooling system.[3]

Background

Cooling Effect of an Evaporative Cooler (EC):

- An EC cools the air by adding humidity to the air at a constant wet bulb temperature.[1]
- As air passes through the EC, evaporating water cools the air due to the latent heat of vaporization.

Effect of Relative Humidity on EC Effectiveness:

- EC systems are less effective at higher humidity levels, reducing their cooling potential due to limited evaporation. (See Figure 3, compared to Figure 2.)

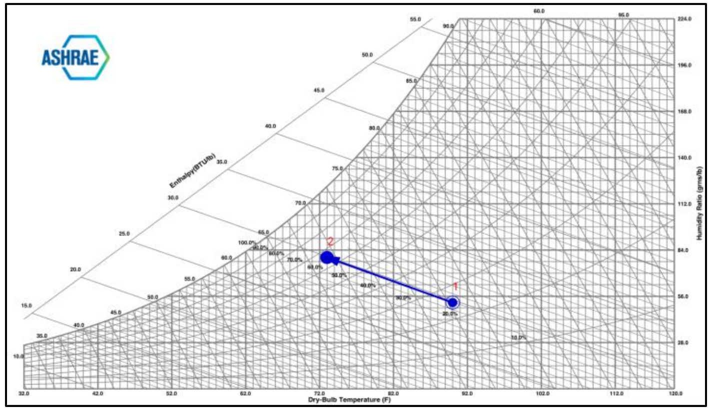


Fig 2. Evaporative cooling (low humidity) psychometric process

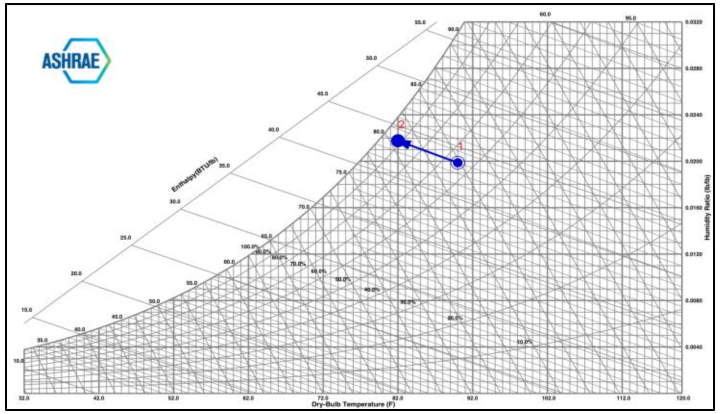


Fig 3. Evaporative cooling (high humidity) psychometric process

Background

Combining EC with a Desiccant Wheel (DW):

- The integration of a rotating desiccant wheel to enhance EC performance has been explored in various studies [6-9] to achieve **significant** humidity reduction and control.
- A desiccant wheel is a device that removes moisture from the air, by absorbing it onto the desiccant material.

Main types of desiccant wheel systems

- Active
- Passive

The one of choice for this project is the **Active** desiccant wheel (in Fig. 4) [10]

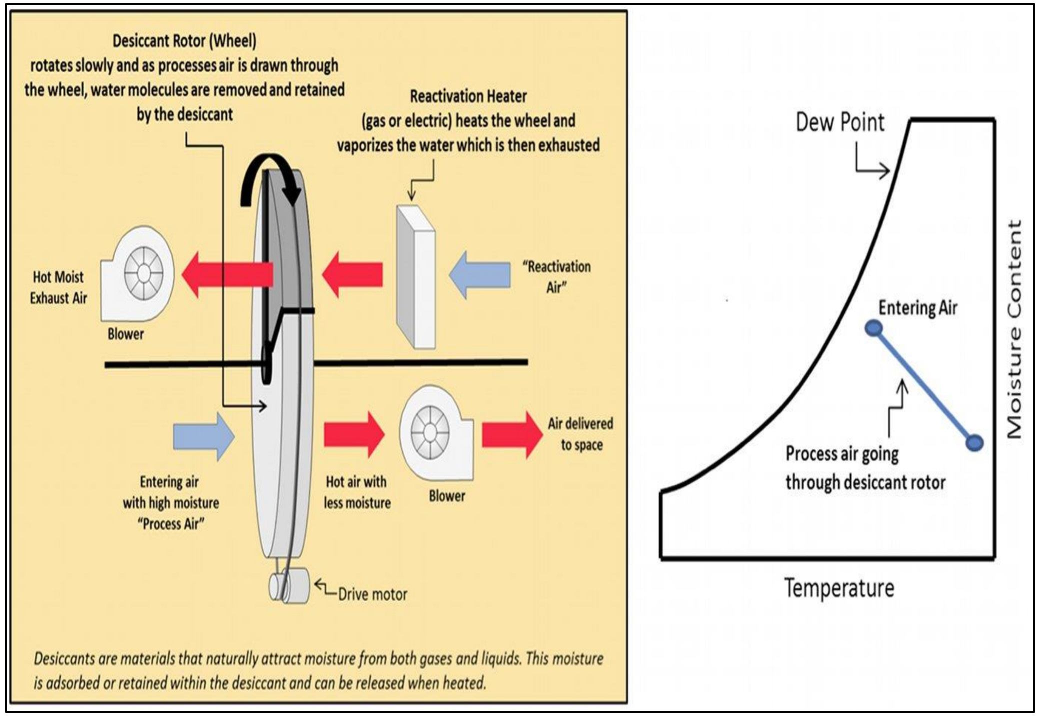


Fig 4. Desiccant Wheel System[9]

Motivation

Evaporative coolers known to work effectively, **in reliably dry climates** [2]**.**

But,

To improve its widespread usage for the diverse US climates, reducing carbon emissions and energy consumption.

What crucially can be done?

- Design a closed-loop control system for residential evaporative cooling AC, managing both temperature and humidity, is currently unavailable in the market.

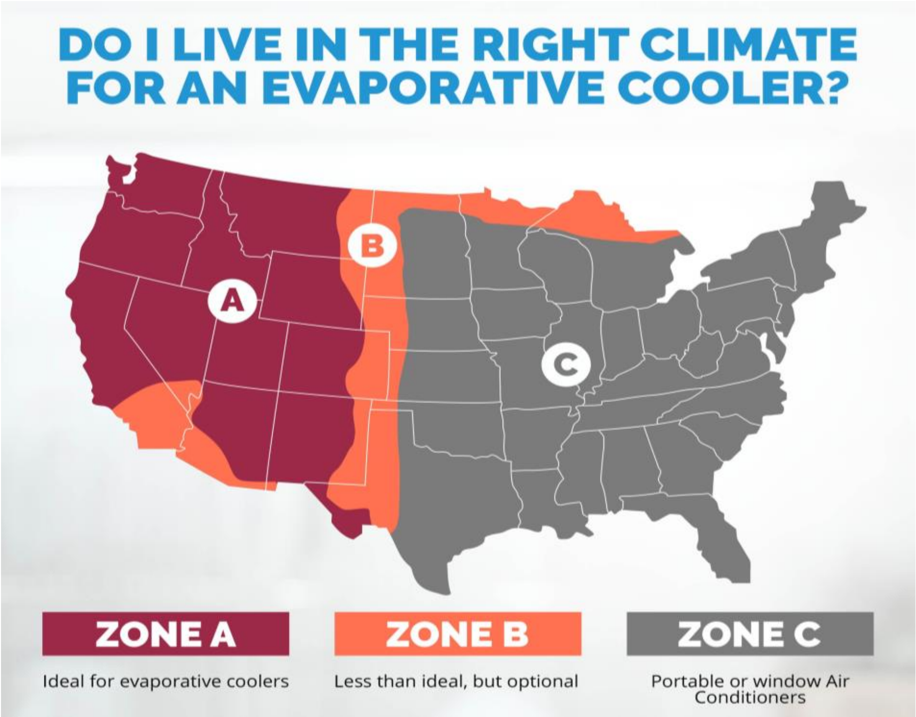


Fig 5. Efficiency of EC systems across the US.
Source: https://www.newair.com/blogs/learn/what-are-evaporative-coolers

Objectives

1. Develop a mathematical model governing the thermal system (house)
2. Design a combined evaporative cooling/desiccant wheel (EC/DW) MIMO system to regulate temperature and humidity in residential applications.
3. Assess and review energy savings by comparing the combined EC and DW system with a standard vapor-compression AC system.

Methodology – Open-Loop Simulink Model

Open loop plant models for $\mathbf{T_H}$ and $\mathbf{W_H}$ of the house space based on the differential equations (ODEs) from system's dynamic energy models for Dry Air and Water Vapor.

A. Dynamic Dry air energy equation

$$\frac{dT_H}{dt} = \frac{1}{\rho_{da}\forall_H Cp_{da}}\left(k(T_o - T_H) + \dot{m}_{s-da}Cp_{da}T_s + \dot{m}_{o-da}Cp_{da}T_o - \dot{m}_{r-da}Cp_{da}T_H\right)$$

B. Dynamic Water Vapor energy equation

$$\frac{dw_H}{dt} = \frac{1}{\rho_w\forall_H}(m_{s-da})w_s + \dot{m}_{o-da}w_o - \dot{m}_{r-da}w_H$$

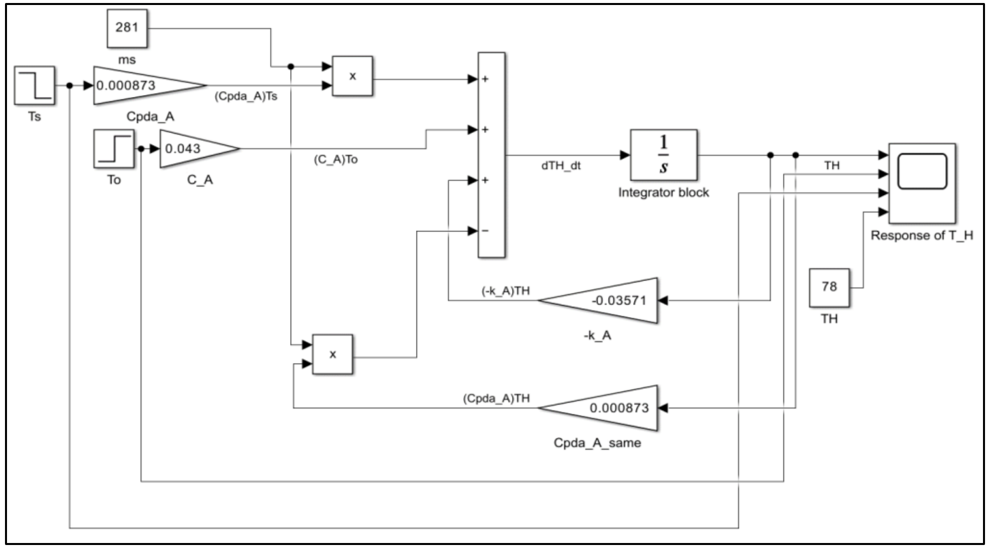


Fig 6. T_H for Open Loop Plant

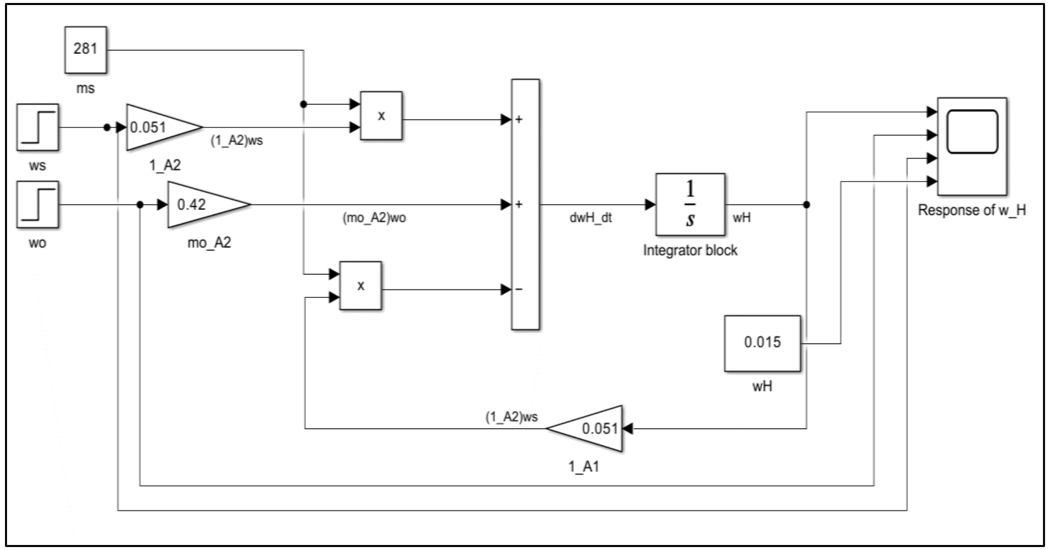
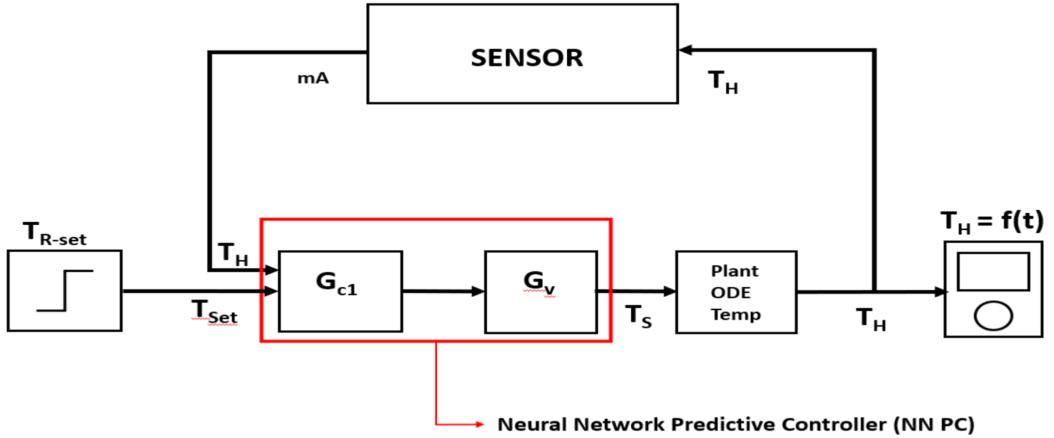


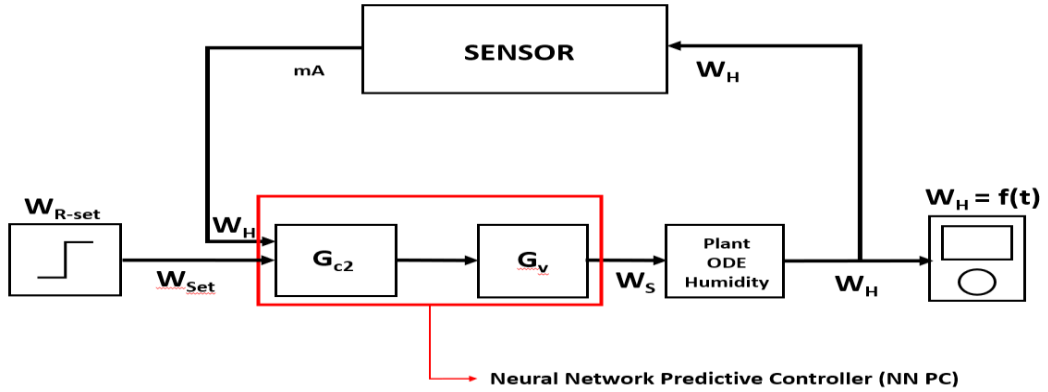
Fig 7. W_H for Open Loop Plant

Methodology – Closed-Loop Block Diagram

Control System Block Diagram for Temperature



Control System Block Diagram for Humidity



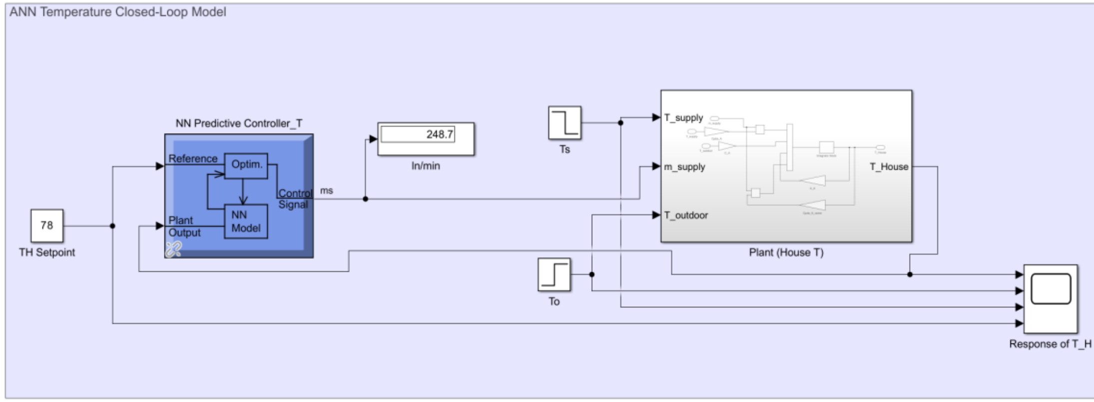


Fig 8. ANN Closed-Loop Simulink Model for T_H

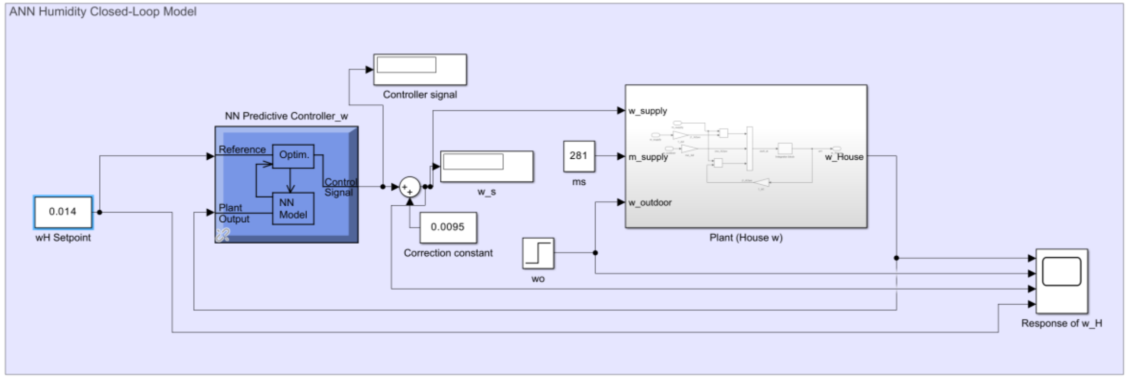
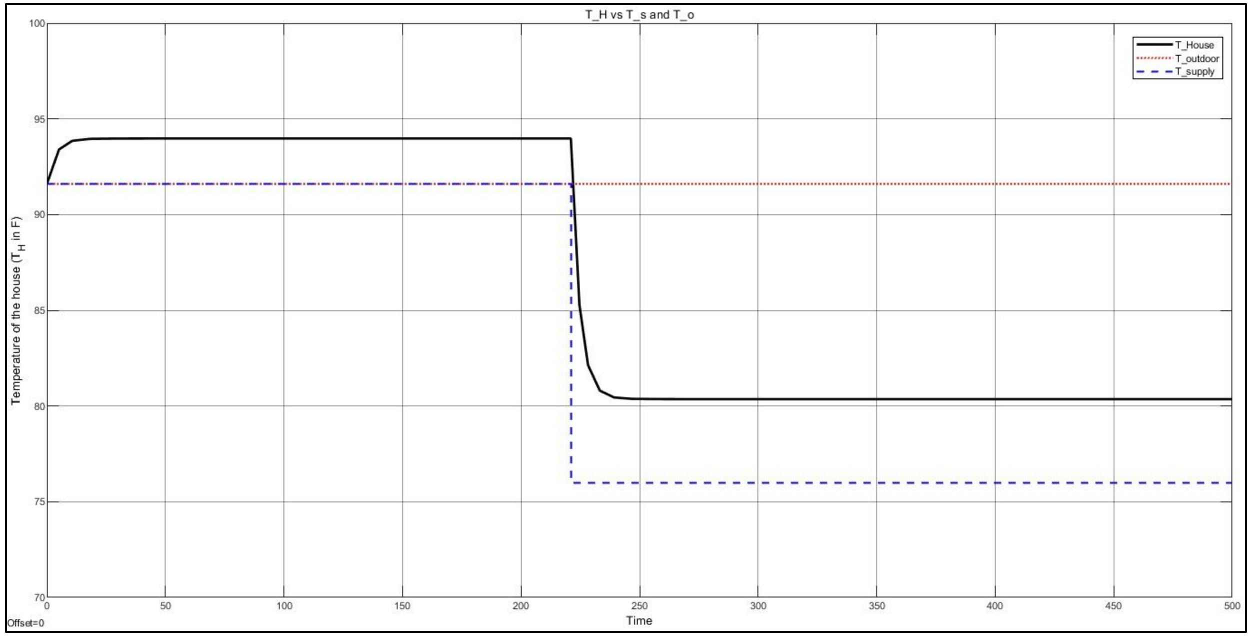


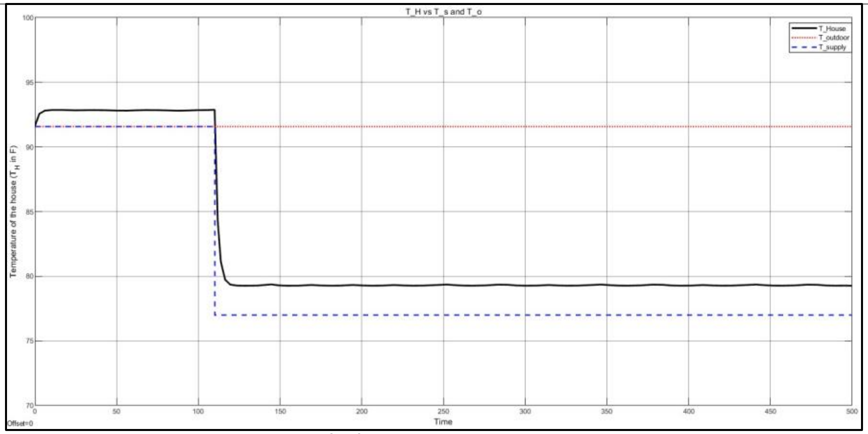
Fig 9. ANN Closed-Loop Simulink Model for T_H

Results and Discussion – Open-Loop Model T_H Responses

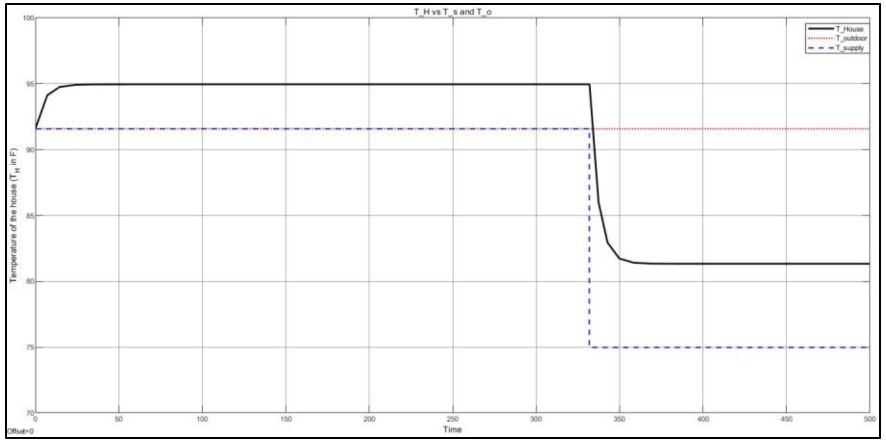
T_H responses for setpoint changes in T_S



(A) Base Line



(B) Increased Ts

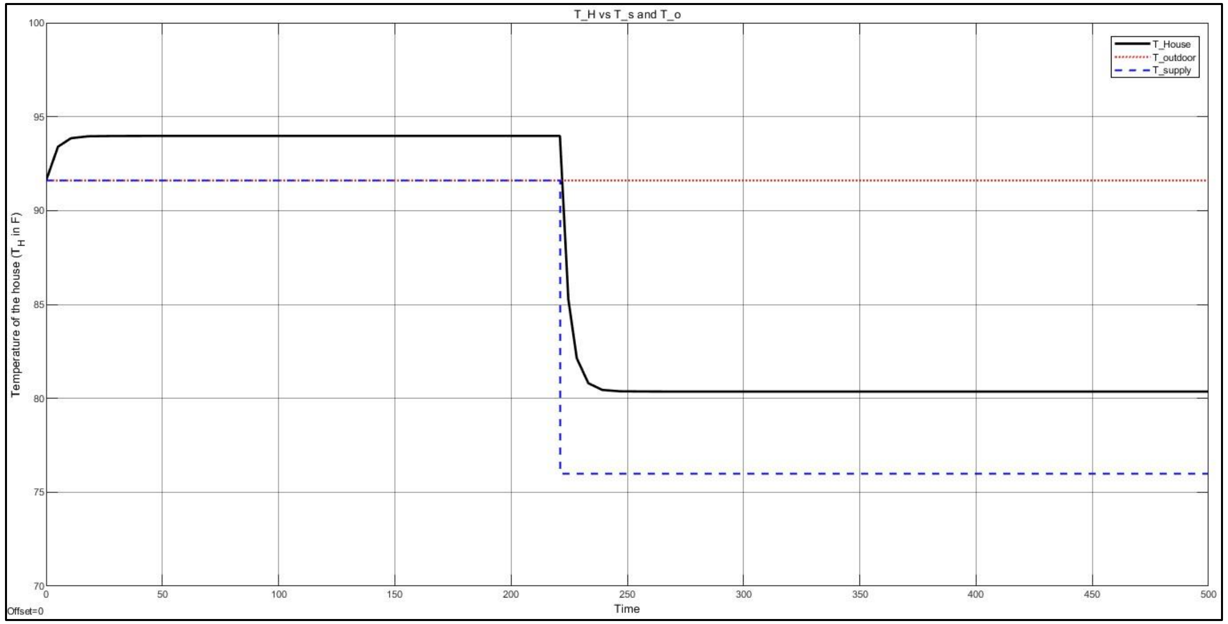


(C) Decreased Ts

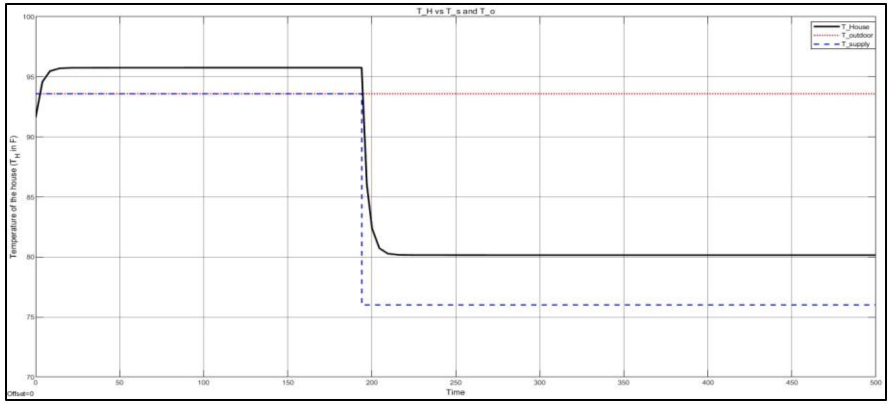
Fig 10. Open-Loop Model Response to T_s changes (A) Base Model (From Annual conditions data) (B) Increased T_s (C) Decreased Ts

Results and Discussion – Open-Loop Model T_H Responses (CONT'D)

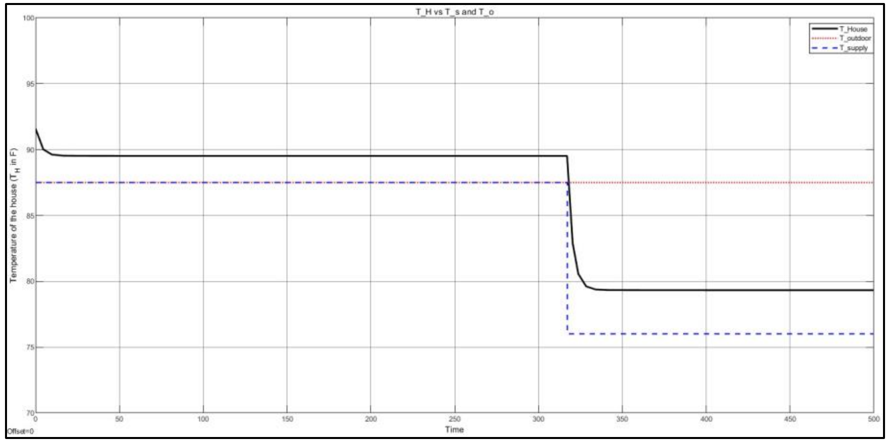
T_H responses for disturbance changes



(A) Base Line



(B) Increased To

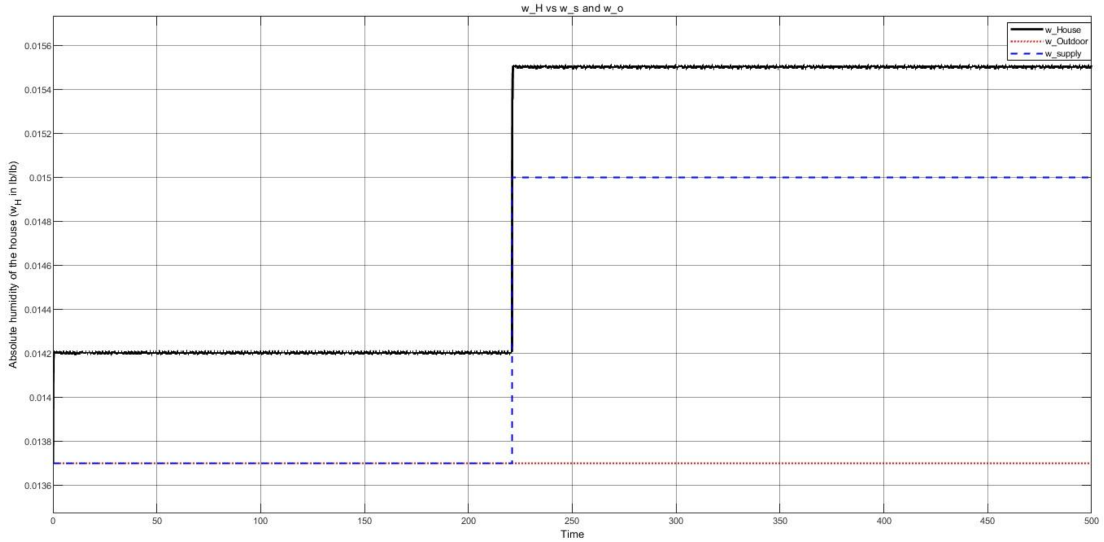


(C) Decreased To

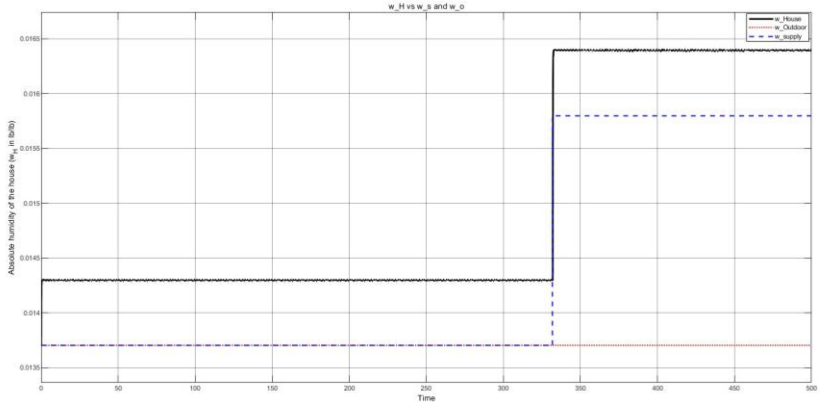
Fig 11. Open-Loop Model Response to T_o changes (A) Base Model (From Annual conditions data) (B) Increased T_o (C) Decreased T_o

Results and Discussion – Open-Loop Model W_H Responses

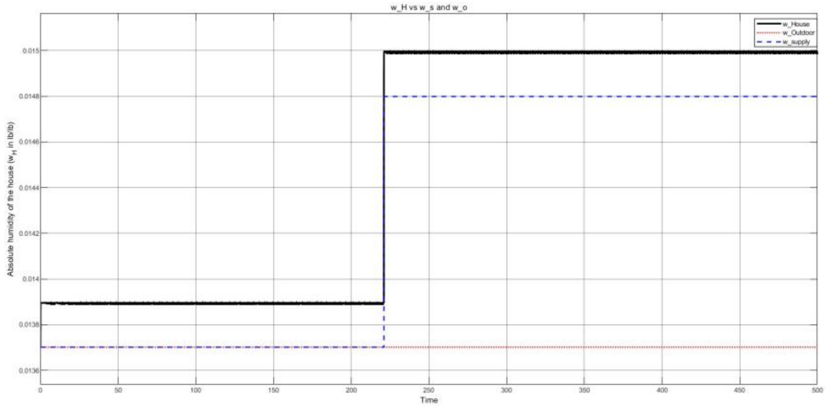
W_H responses for setpoint changes in W_S



(A) Base Line



(B) Increased W_s

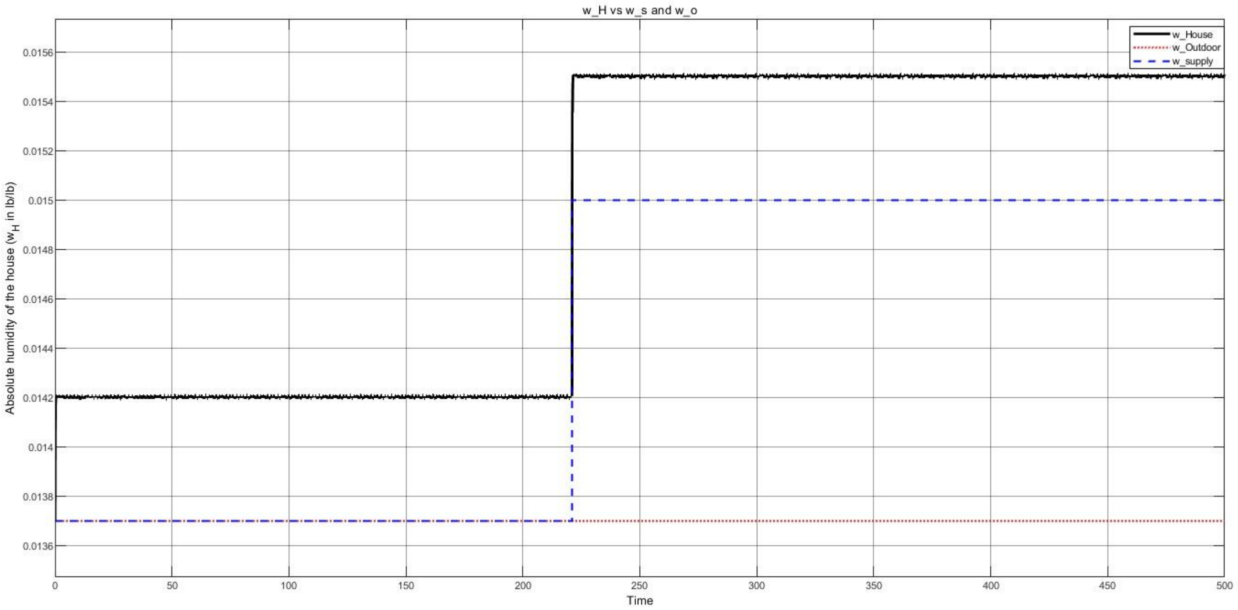


(C) Decreased W_s

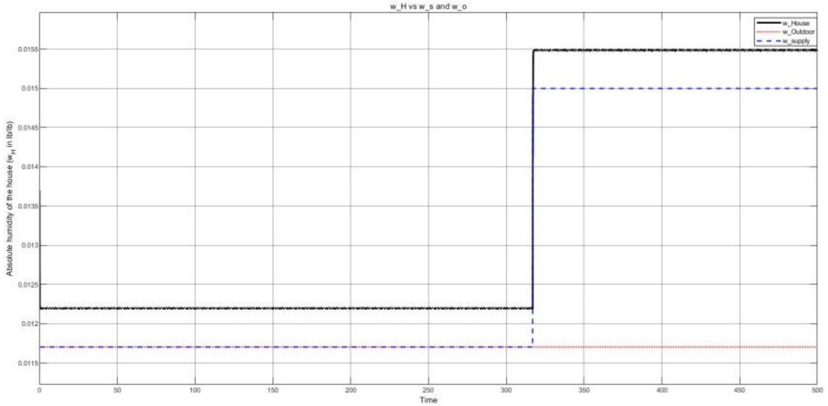
Fig 12. Open-Loop Model Response to W_s changes (A) Base Model (From Annual conditions data) (B) Increased W_s (C) Decreased W_s

Results and Discussion – Open-Loop Model W_H Responses (CONT'D)

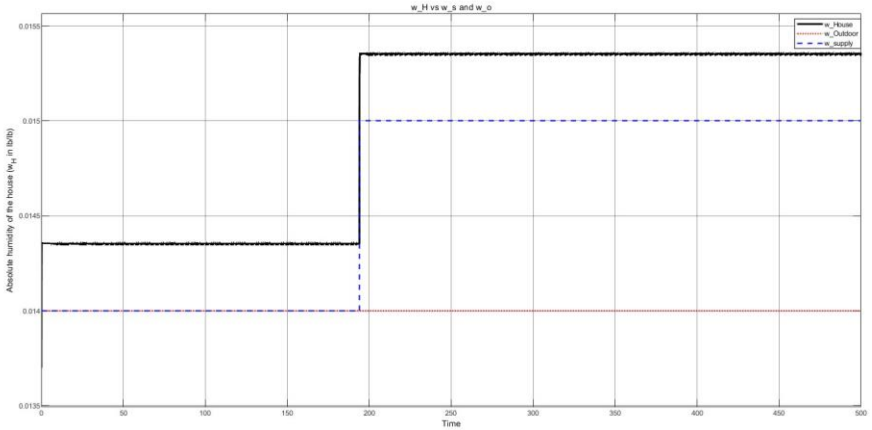
W_H responses for disturbance changes



(A) Base Line



(B) Increased W_o

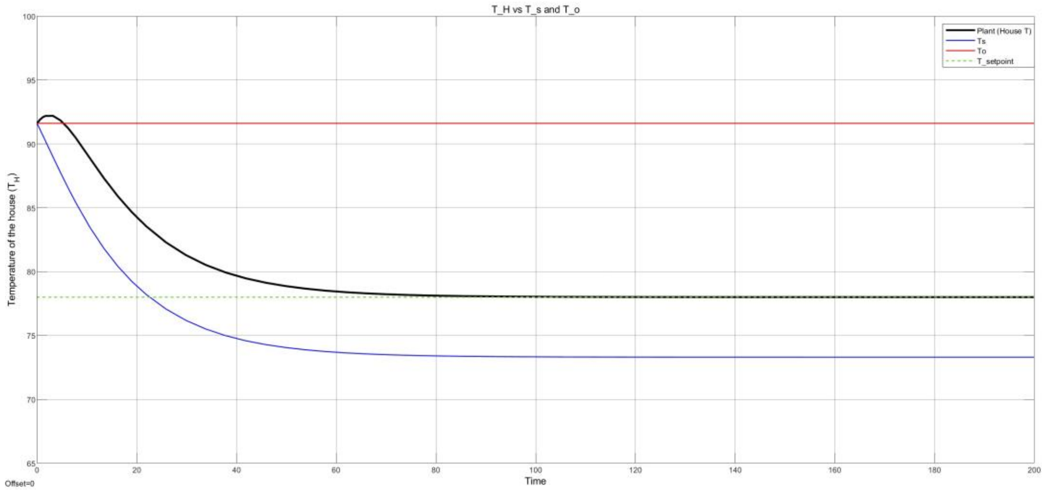


(C) Decreased W_o

Fig 13. Open-Loop Model Response to W_o changes (A) Base Model (From Annual conditions data) (B) Increased W_o (C) Decreased W_o

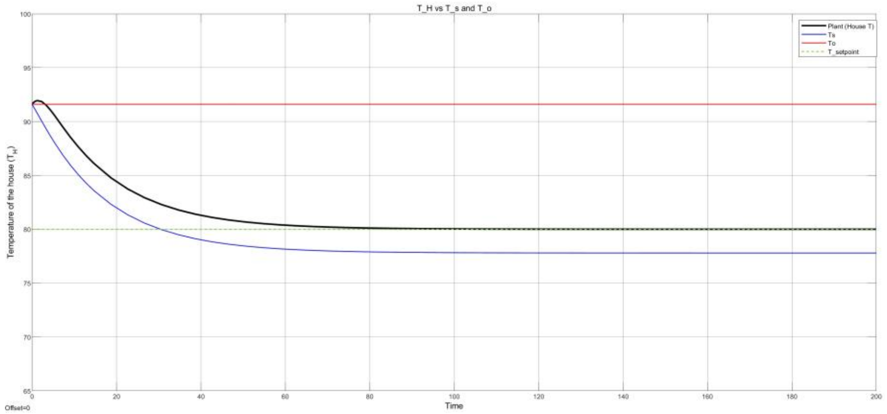
Results and Discussion – Closed-Loop PID Model T_H Responses

T_H responses for setpoint and disturbance changes

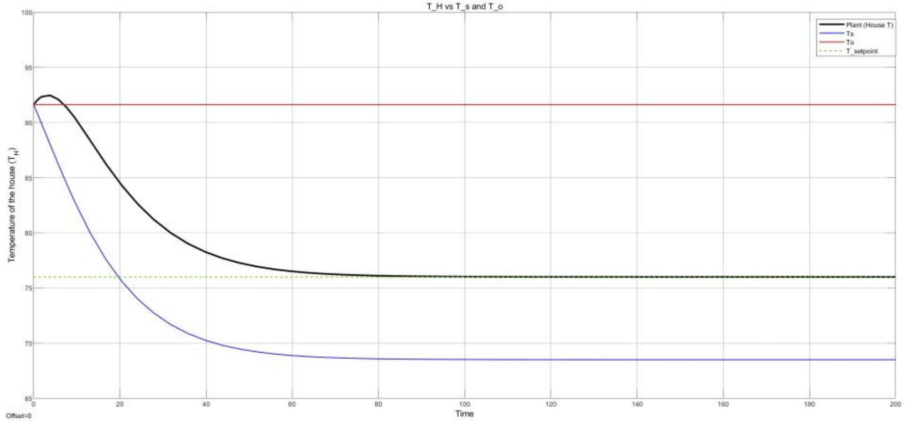


(A) Base Line

Fig 14. Closed-Loop Model Response to T_{set} changes (A) Base Model (From Annual conditions data) (B) Increased T_{set} (C) Decreased T_{set}



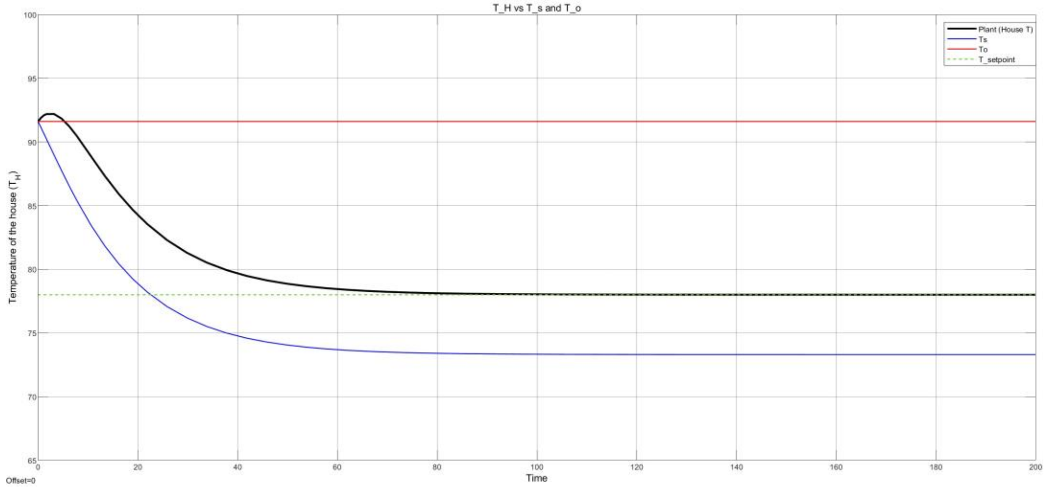
(B) Increased T_{set}



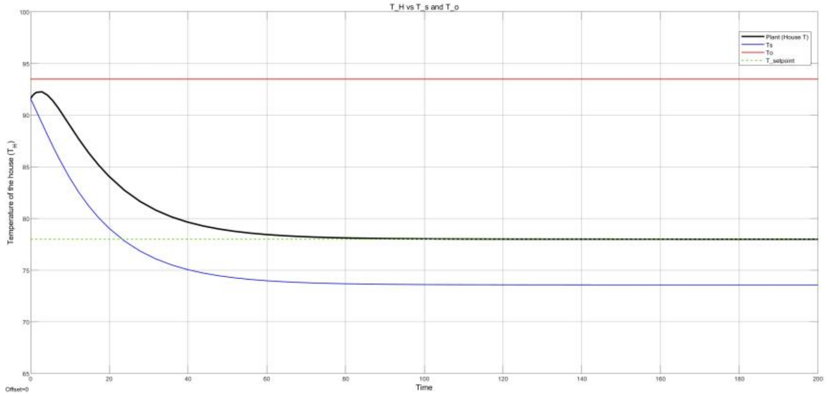
(C) Decreased T_{set}

Results and Discussion – Closed-Loop PID Model T_H Responses (CONT'D)

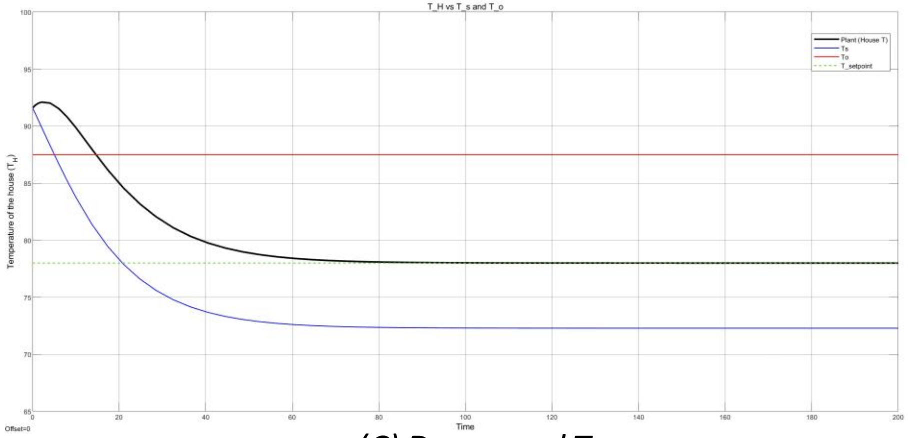
T_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased T_O

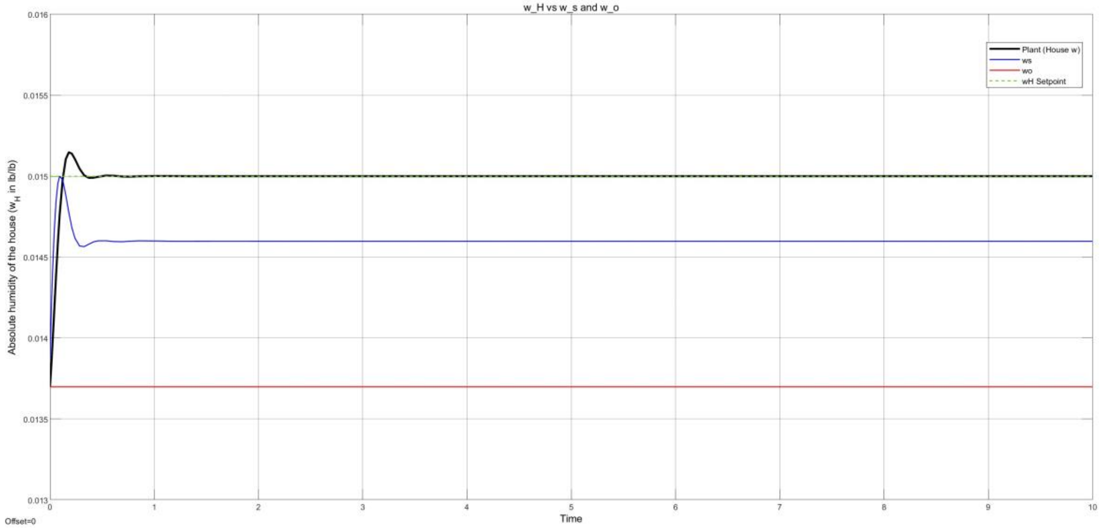


(C) Decreased T_O

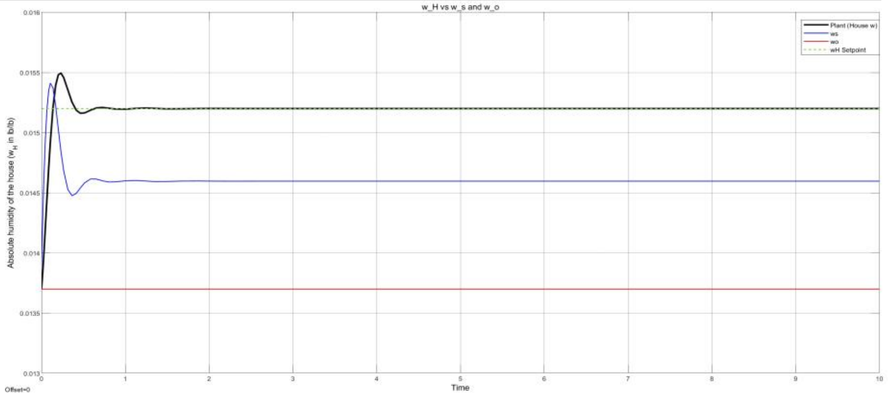
Fig 15. Closed-Loop Model Response to T_o changes (A) Base Model (From Annual conditions data) (B) Increased T_o (C) Decreased T_o

Results and Discussion – Closed-Loop PID Model W_H Responses

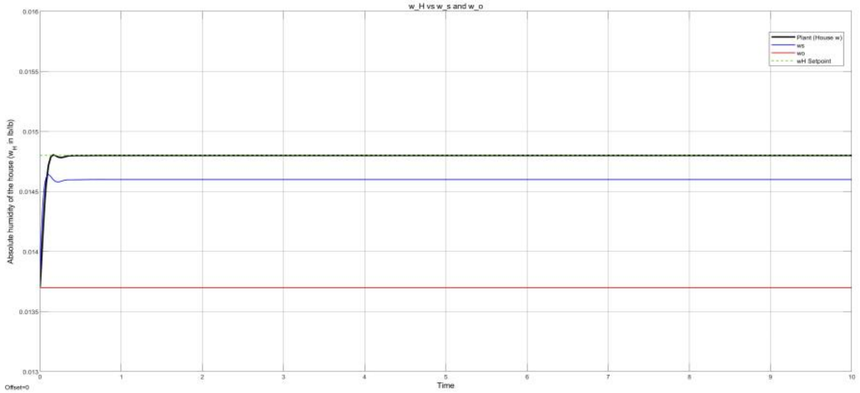
W_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased W_{set}

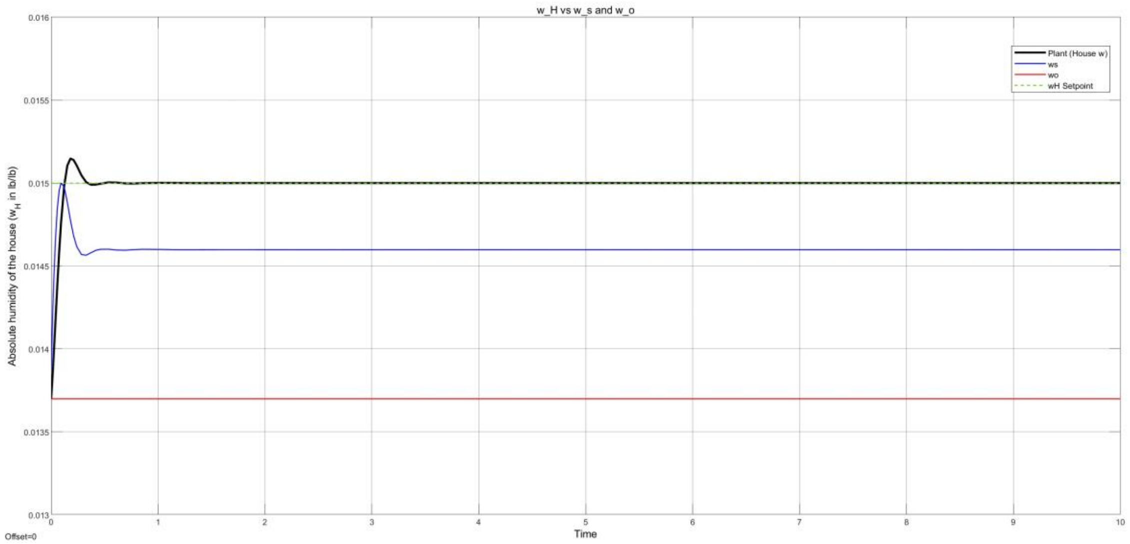


(C) Decreased W_{set}

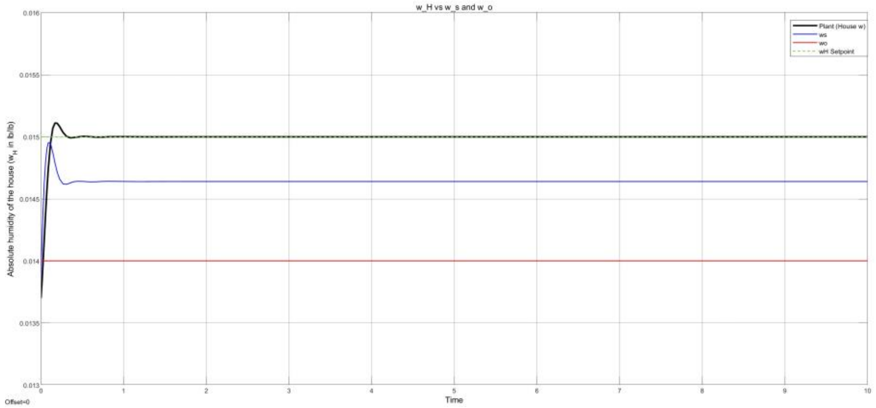
Fig 16. Open-Loop Model Response to W_{set} changes (A) Base Model (From Annual conditions data) (B) Increased W_{set} (C) Decreased W_{set}

Results and Discussion – Closed-Loop PID Model W_H Responses (CONT'D)

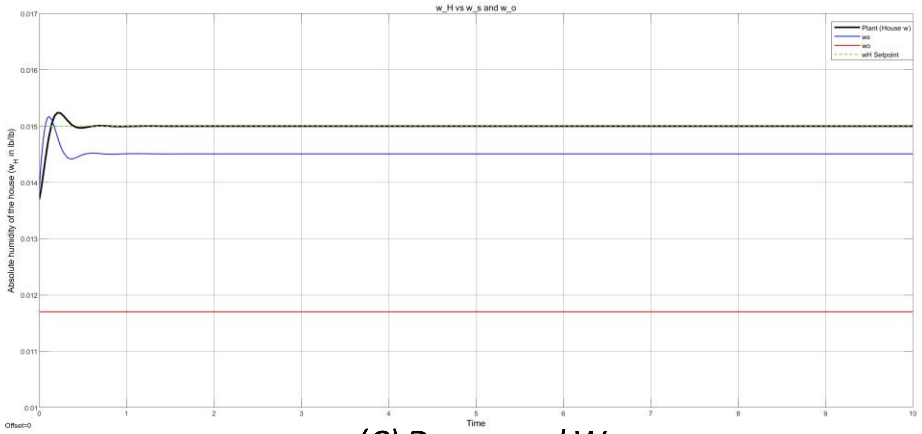
W_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased W_O

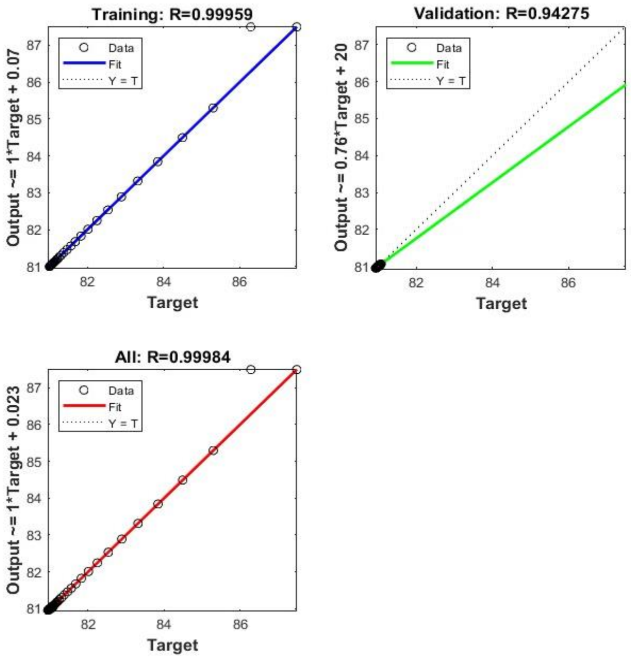


(C) Decreased W_O

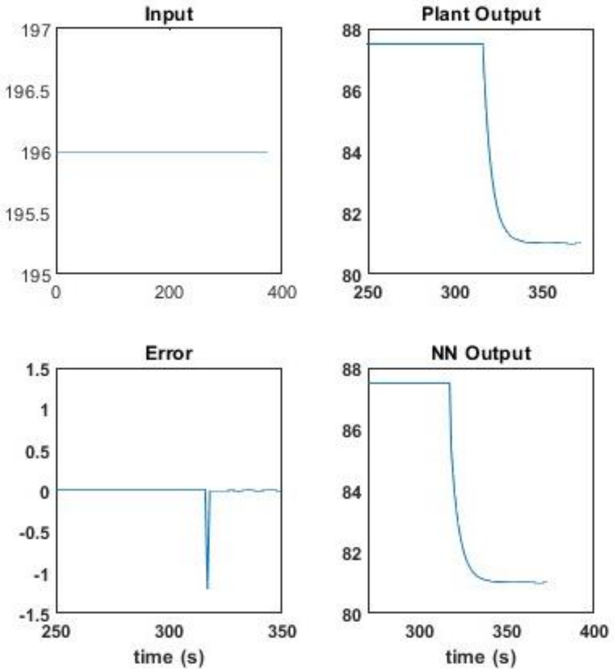
Fig 22. Closed-Loop Model Response to W_o changes (A) Base Model (From Annual conditions data) (B) Increased W_o (C) Decreased W_o

Results and Discussion – ANN Plots for Temperature

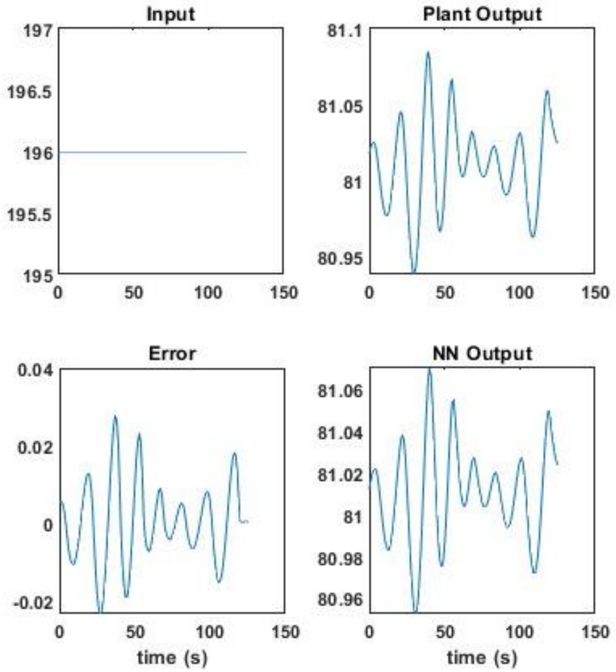
- Training model for ANN 3X based on T setpoint and disturbance changes, as elaborated in previous slide



(A) Regression Plot (40 neurons)



(B) Response Plot (40 neurons)

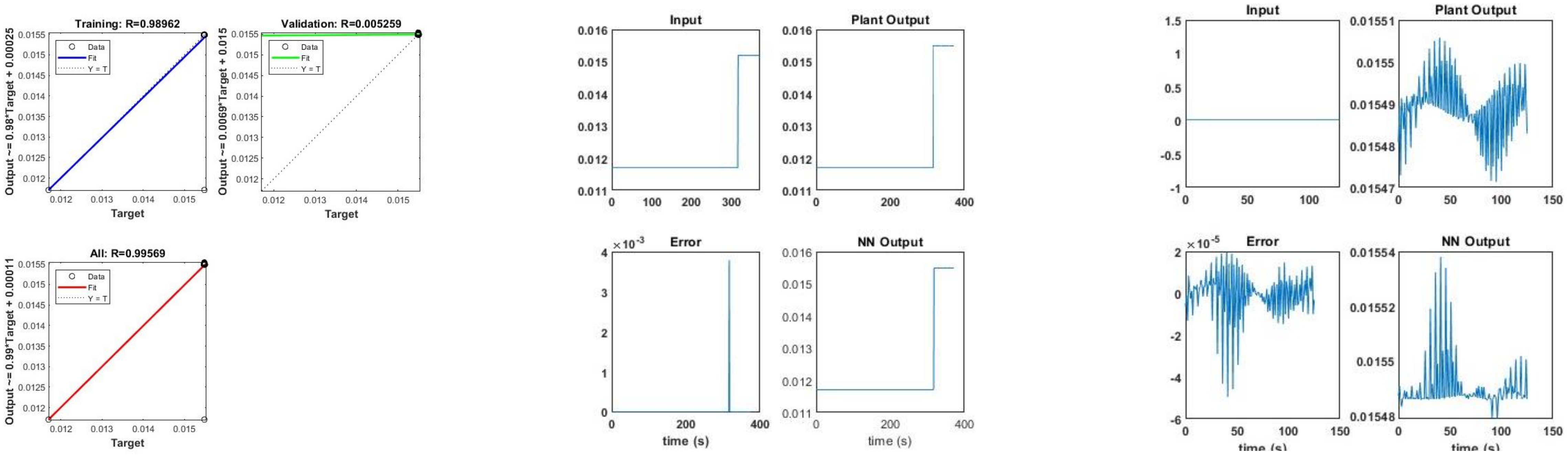


(C) Validation Plot (40 neurons)

Fig 14. ANN plots for Temperature

Results and Discussion – ANN Plots for Humidity

- Training model for ANN 3X based on W setpoint and disturbance changes



(A) Regression plot (35 neurons)

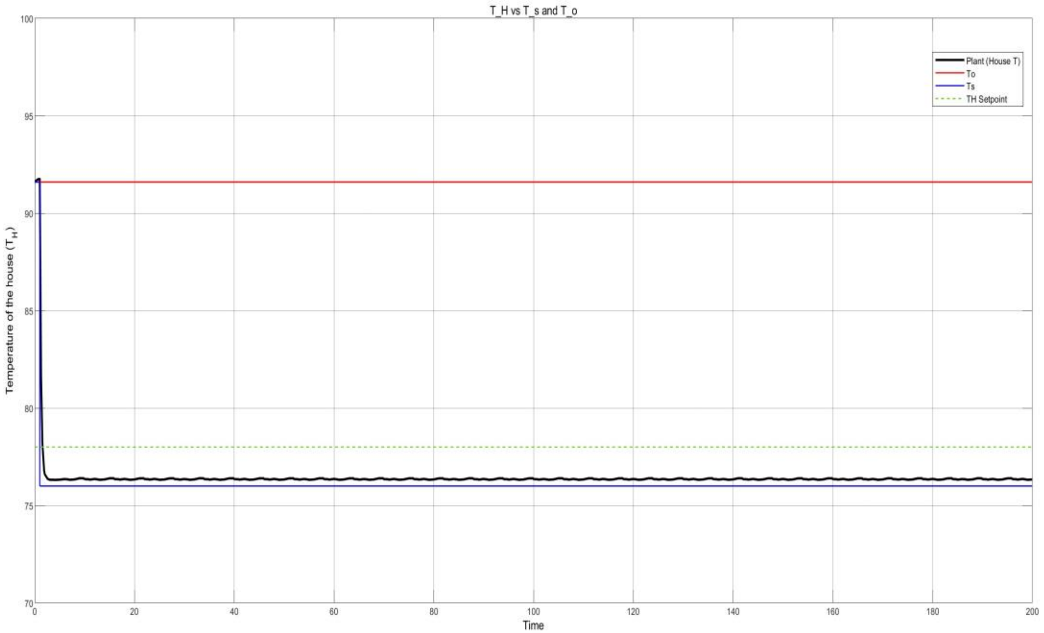
(B) Response plot (35 neurons)

(C) Validation (35 neurons)

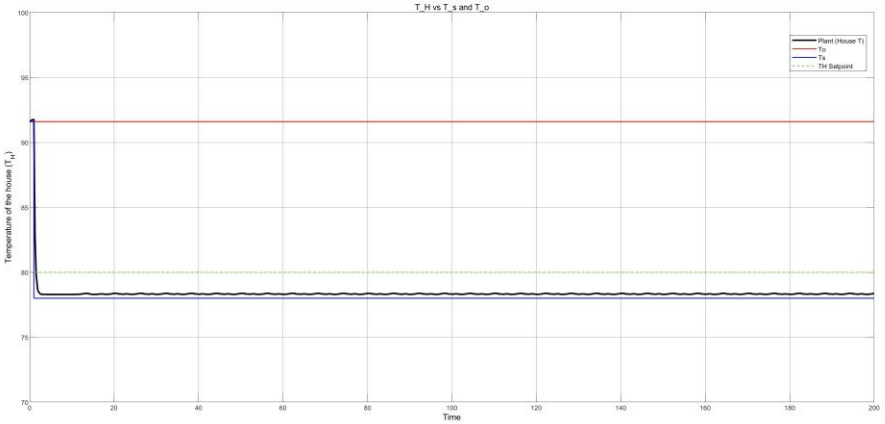
Fig 15. ANN plots for Humidity

Results and Discussion – Closed-Loop Model T_H Responses

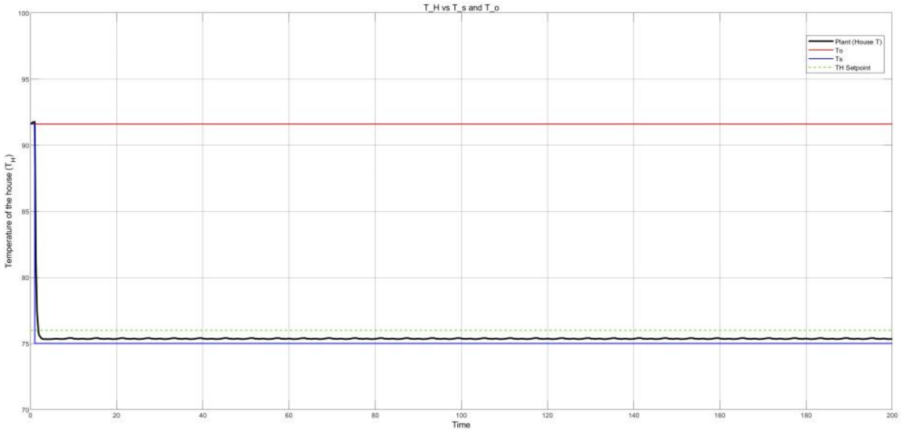
T_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased T_{set}

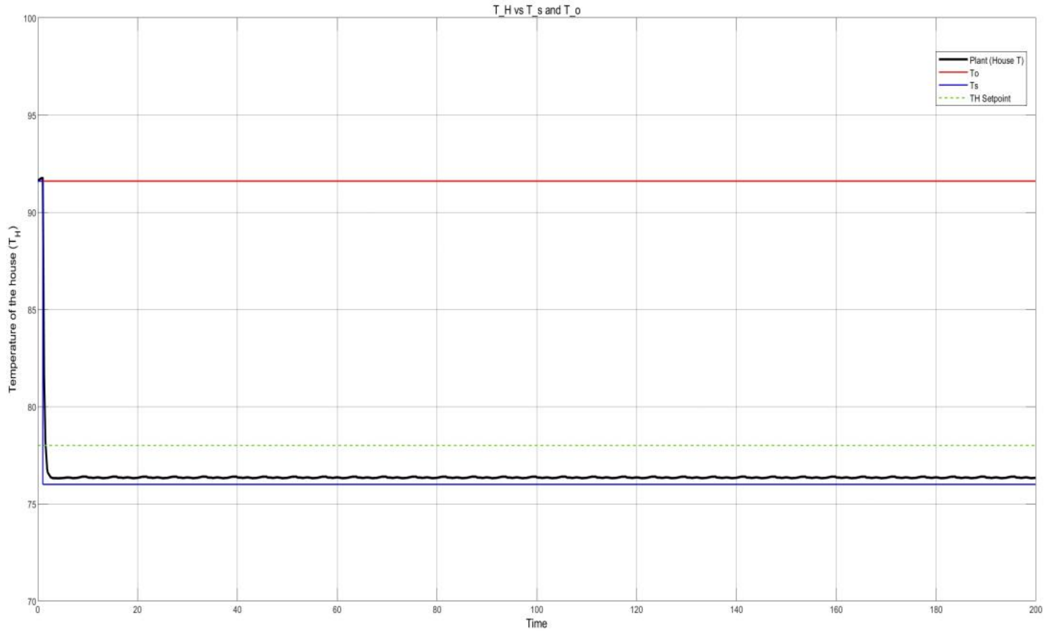


(C) Decreased T_{set}

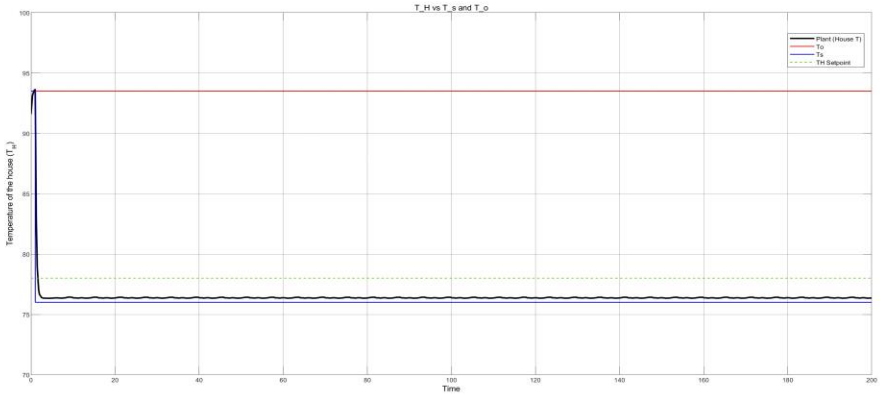
Fig 19. Closed-Loop Model Response to T_{set} changes (A) Base Model (From Annual conditions data) (B) Increased T_{set} (C) Decreased T_{set}

Results and Discussion – Closed-Loop Model T_H Responses (CONT'D)

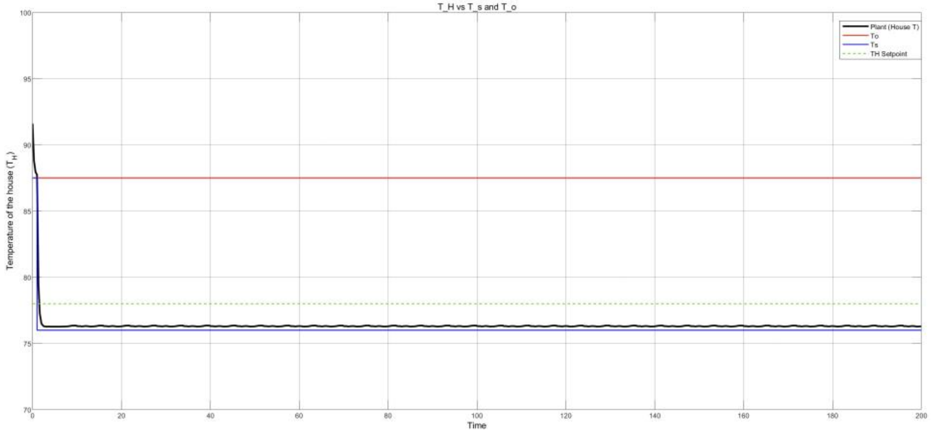
T_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased T_O

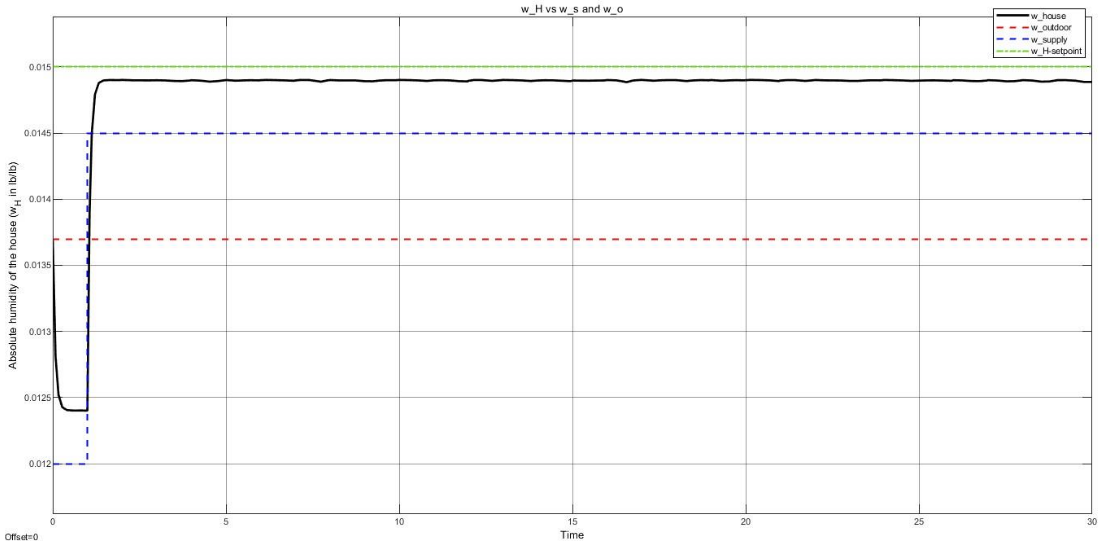


(C) Decreased T_O

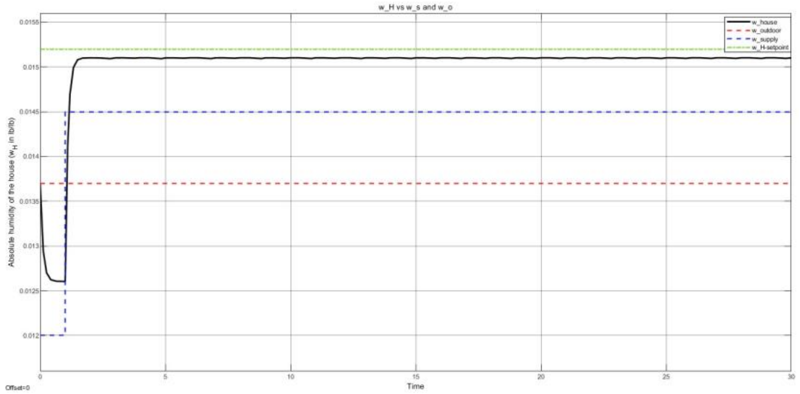
Fig 20. Closed-Loop Model Response to T_o changes (A) Base Model (From Annual conditions data) (B) Increased T_o (C) Decreased T_o

Results and Discussion – Closed-Loop Model W_H Responses

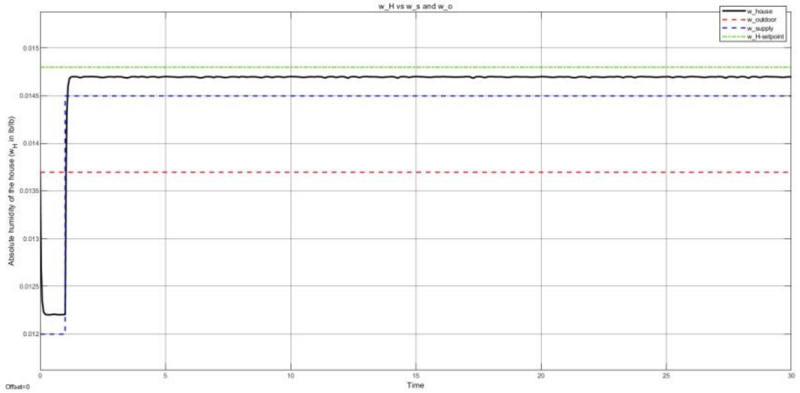
W_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased W_{set}

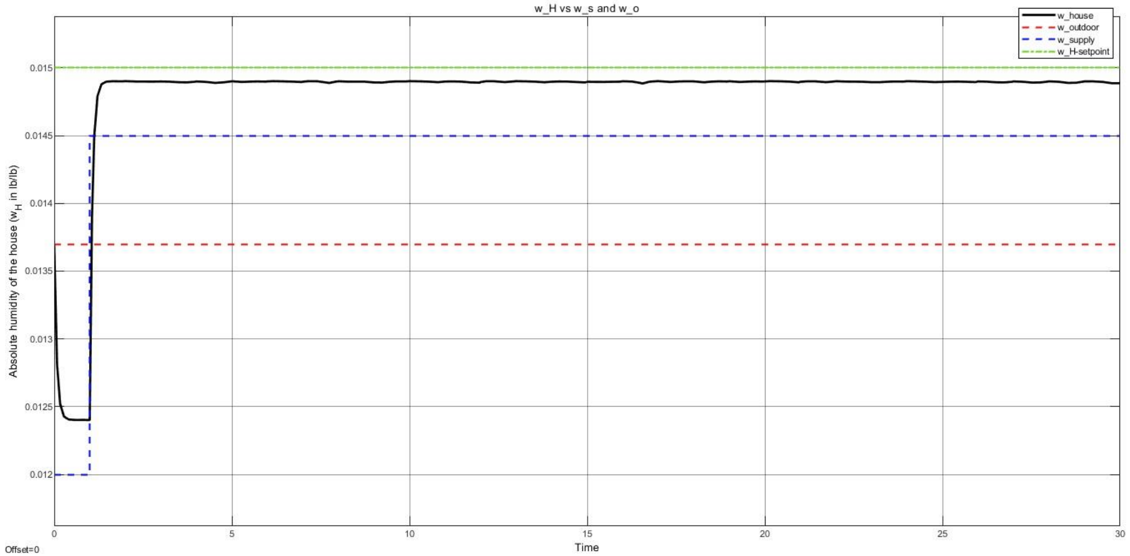


(C) Decreased W_{set}

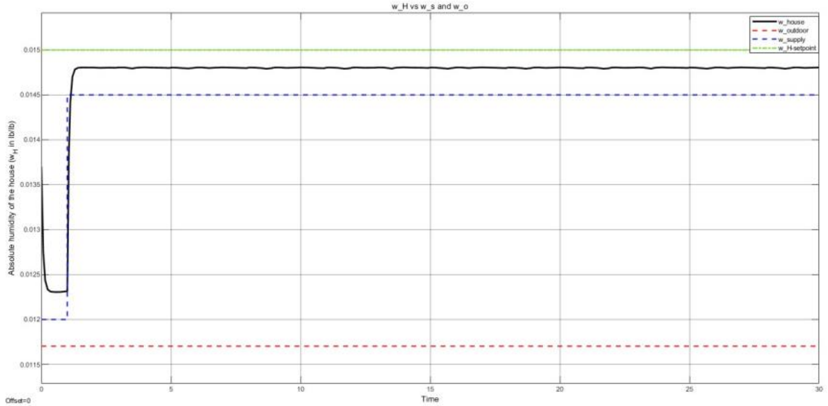
Fig 21. Open-Loop Model Response to W_{set} changes (A) Base Model (From Annual conditions data) (B) Increased W_{set} (C) Decreased W_{set}

Results and Discussion – Closed-Loop Model W_H Responses (CONT'D)

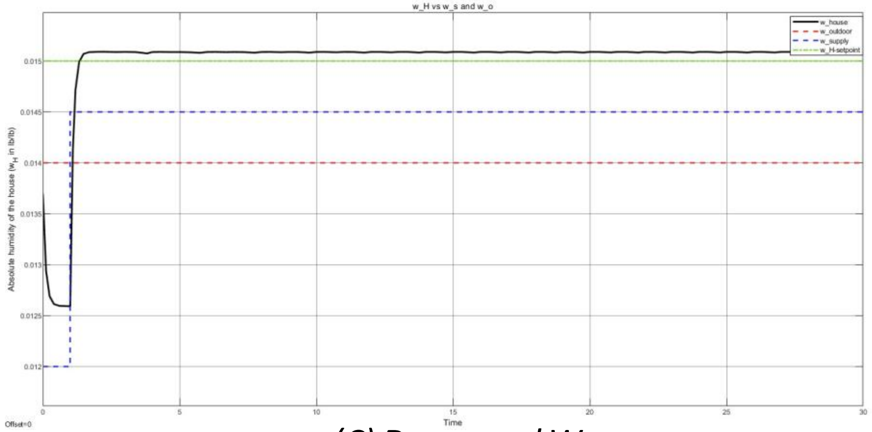
W_H responses for setpoint and disturbance changes



(A) Base Line



(B) Increased W_O



(C) Decreased W_O

Fig 22. Closed-Loop Model Response to W_o changes (A) Base Model (From Annual conditions data) (B) Increased W_o (C) Decreased W_o

Results and Discussion – Economic, Sustainability & Innovation Comparison

Rubric: 1 – Very Low 2 – Low 3 – Normal 4 – High 5 – Very High

Factor	Standard AC	Proposed	Reason
Operational Cost	High	Very Low	• Typical low maintenance costs for EC systems. • Main fluid in the governing process is water. • Low electrical consumption for Desiccant Wheel (DW) and blower motors because of the very low RPM needed.
Emissions/ Environment Concerns	Very High	Very Low	• Lower energy usage, thus contributing to a lower carbon footprint. • A typical evaporation cooling unit has been found to be capable of reducing $C0_2$ emissions by up to 80% [8]. • No hydrocarbon-based coolants being released into the environment.
Innovative Factor	Normal	High	• Proposed system with Temperature and Humidity control will be a novel system on the market.

Conclusion and Future Recommendations

In Conclusion,

- Developed a residential thermal dynamics model for control of temperature and humidity.
- Introduced an adaptable EC/DW MIMO system for residential spaces, suitable for diverse climates.
- Conducted a comparison and assessment, revealing significant benefits to energy and sustainability compared to vapor-compression AC systems

Future Recommendations

- Explore proposed system integration with renewable energy sources, further enhancing sustainability.
- Research advanced materials and technologies for improved efficiency and durability of the EC/DW system.
- A more in-depth search into control hardware to implement ANN model

References

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Thank you!

Appendix A – Files & Video Presentation link

Video

https://uthsct.sharepoint.com/sites/ProcessControlCourseProject/Shared%20Documents/General/Recordings/Meeting%20in%20_General_-20231207_231634-Meeting%20Recording.mp4?web=1

Simulink and MATLAB models

Open and closed loop models

All relevant project documents

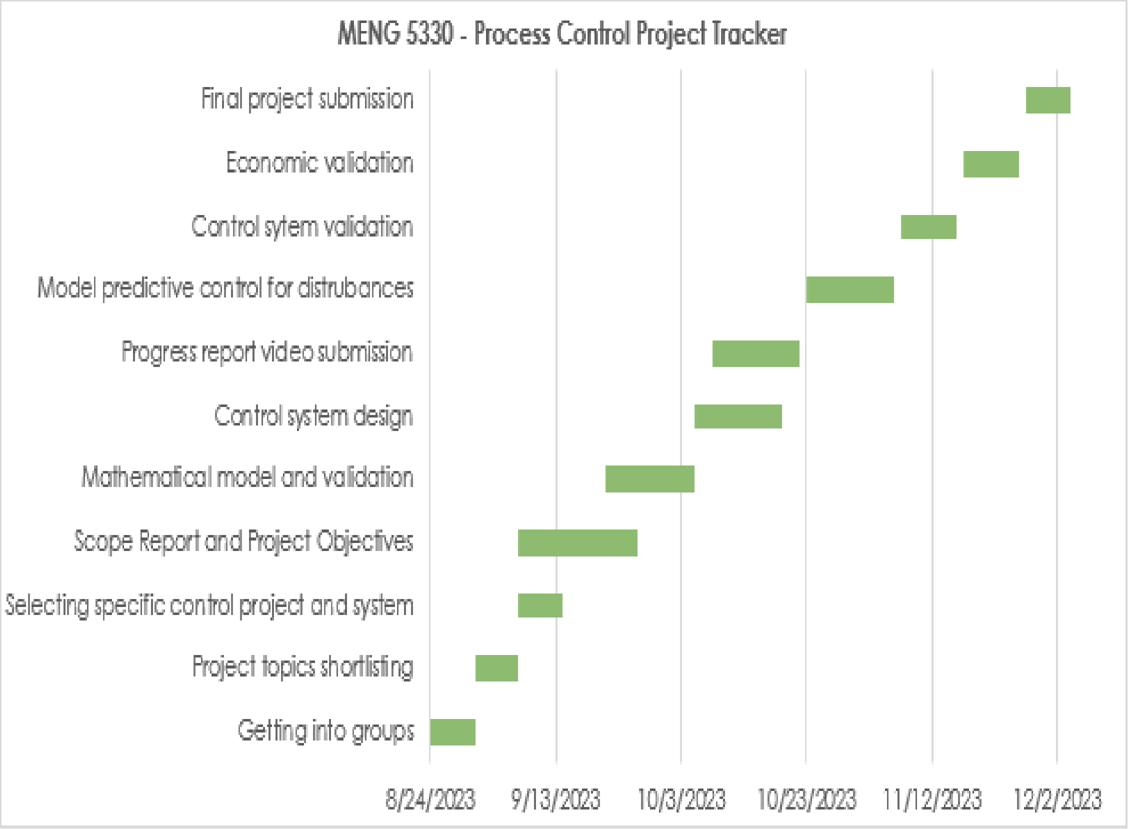
Project documents

Appendix B – Gantt Chart

SETUP

Percent Over/Under to Flag 100%

Task	Estimated Start	Estimated Finish	Estimated Work (in hours)	Estimated Duration (in days)	Actual Work (in hours)	Notes
Getting into groups	8/24/2023	8/31/2023	4	7	6	**Completed**
Project topics shortlisting	8/31/2023	9/7/2023	4	7	7	Completed
Selecting specific control project and system	9/7/2023	9/14/2023	4	7	6	Completed
Scope Report and Project Objectives	9/7/2023	9/26/2023	12	19	**25**	Completed
Mathematical model and validation	9/21/2023	10/5/2023	9	14	**40**	Completed
Control system design	10/5/2023	10/19/2023	9	14	**32**	Completed
Progress report video submission	10/8/2023	10/22/2023	9	14	**25**	Completed
NN predictive control for distrubances	10/23/2023	11/6/2023	9	13	**35**	Completed
Control sytem validation	11/7/2023	11/16/2023	5	9	**20**	Completed
Economic validation	11/17/2023	11/26/2023	5	9	10	Completed
Final project submission	11/27/2023	12/7/2023	6	10	**30**	Completed



Appendix C – New Relevant Changes Made from Progress Report

Changes Based On Instructor Feedback

- Implemented ANN Empirical Model
- References were modified completely to meet IEEE referencing style standards
- Clearly defined inputs and references in response plots
- Graphs labels are shown
- Contents in Results and Methodology slides from previous report have been rectified

Changes Completed As Project Requirements

- Implemented ANN Empirical Model
- Perform the controller design with appropriate assumptions
- Completed a quality oral video report

Changes / Additions Based On Project Objectives and Team's Preferred Changes

- New plant model based on ODE with Initial conditions
- Energy savings assessment and comparison between standard AC system and Proposed EC/DW system.
- Future Recommendations on Project

III. VIDEO REPORT CHECKLIST

Name: Giovanni Cerrato, Amrit Thapa, Gideon Nyarko

Please complete this checklist and include in Appendix when you submit the pdf file for this report in Canvas course.

_X_   I have addressed all parts of the assignment.

_X__   I have met course expectations and requirements and solve some of the given set of problems/questions.

_X__   I have defined Project Motivation and Objectives

_X__   I have sufficient pertinent literature review (~10 publications) for to meet the project objective(s) for Background and References

_X_ I have described some Specifications, Constraints, Limitations, etc. relevant to Background or Methodology

_X__   I have appropriate design steps (both synthesis and analysis) with thorough considerations and explanation of economic, environmental or societal contexts (relevant to Results and Discussion).

_X__   Most ideas in every section are logically developed and directly linked to the main point of the section. Most ideas in every section are connected by transitions.

_X__   Oral presentation has clear and appropriate syntax, diction, tone, and non-verbal elements.

_X__   The visual, audio, or other presentation materials meet professional standards, are integrated into the presentation, and do not substitute for but instead balance oral components.

_X__   My presentation meets the time limit.

_X__   I have revised my paper _10_ times to improve its organization, structure, and style as needed.

_X__   I have created a video link to be included in Appendix.

_X__   I have not used anyone else's work, ideas, or language without citing them appropriately

_X_ All my sources are in References slide(s), which is properly formatted in IEEE style.

_X__   I have read the plagiarism statement in the syllabus, understand it, and agree to abide by the definitions and penalties described in the course. (Note: Unicheck will be used to via Canvas to check if <25%, which cannot be exceeded to avoid penalties, for plagiarism and similarities)

_X__   I have created, updated and included Gantt Chart in Appendix.

_X__   I have completed this checklist and included it in Appendix.

Student Signature: Giovanni Cerrato, Amrit Thapa, Gideon Nyarko

Date: 12/07/2023

Appendix D – Video Check List

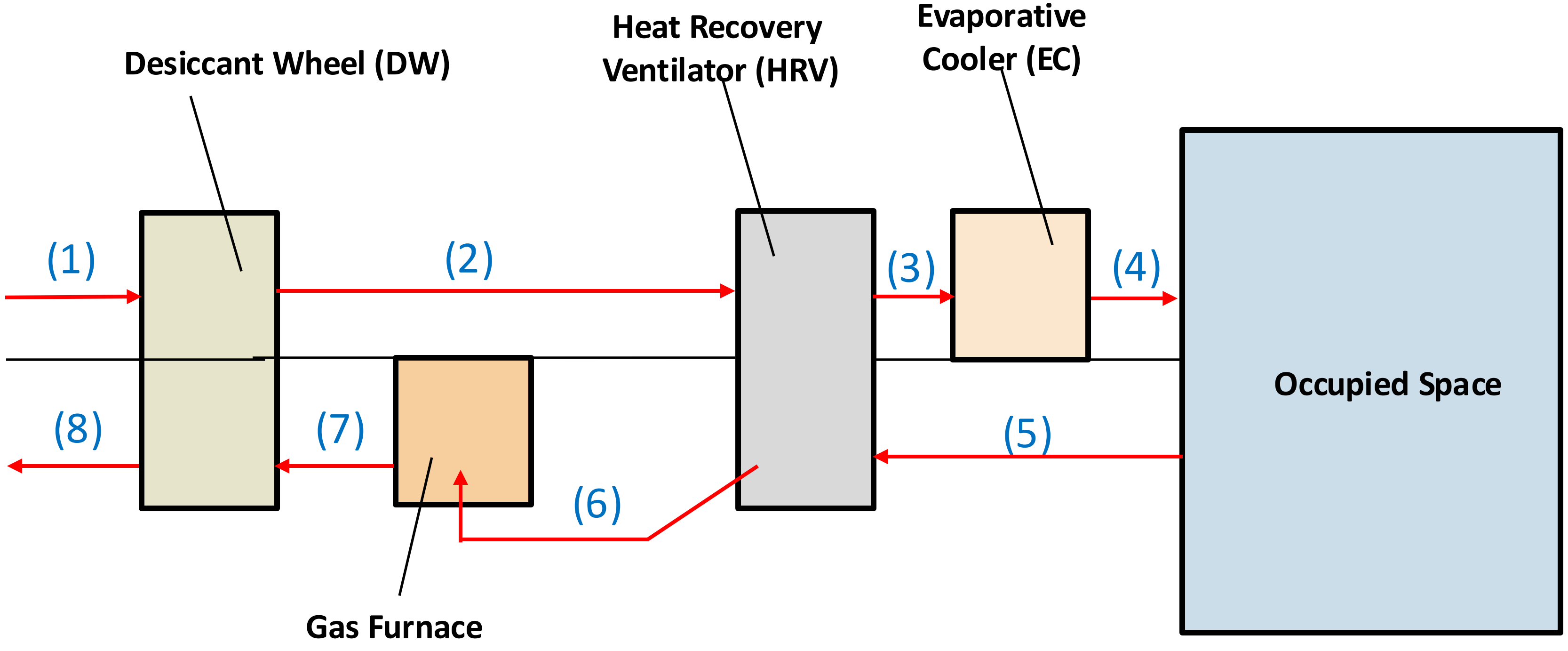
Appendix E - Methodology (System Schematic)

PROPOSED EC AND DW AC SYSTEM

- (1-2) Dehumidification by DW
- (2-3) Sensible Heat Exchange
- (3-4) Direct Evaporative Cooling
- (4-5) Conditioned Space Cooling

After Recirculation

- (5-6) Sensible Heat Exchange
- (6-7) Gas Furnace Air heating
- (7-8) DW regeneration with Hot Dry Air



1 – Outdoor air
2 – Dry air
3 – Cool dry air
4 – Cold humid air into room
5 – Cool humid air exhaust
6 – Mild heated less humid air
7 – Hot dry air from furnace
8 – Hot humid air

Appendix F - Methodology (Load Calculations of Space)

$$\text{Latent Heat Load}: Q_L = (W_o - W_H) M_{o-da} h_{fg} + (W_H - W_{Ec}) M_{s-da} h_{fg}$$

$$\text{Sensible Heat Load}: Q_s = K (T_o - T_H) + M_{o-da} Cp_{da} (T_o - T_H);\ K = (UA)_{House-Total}$$

$$\text{Envelope Heat Transfer Coefficient}:$$

$$K = \{(A_{window} U_{window}) + (A_{roof} U_{roof}) + (A_{wall} U_{wall})\ (A_{floor} U_{floor}) + (A_{door} U_{door})\}$$

$$\text{Sensible Heat Ratio}: SHR = \frac{Q_S}{Q_T} = \frac{Q_S}{Q_S + Q_L}$$

Supply Volumetric flowrate required to maintain setpoint T : $CFM = \frac{Q_S}{1.08(T_H - T_S)}$

Appendix G - Methodology (Dynamic Model of Space)

Dynamic Dry air energy equation

$$\frac{d(\rho V Cp{-}da\ T)}{dt} = K(T_o - T_H) + M_{s-da}h_s + M_{o-da}h_o - m_{r-da}h_H$$

$$\frac{dT_H}{dt} = \frac{1}{\rho_{da}\forall_H Cp_{da}}(k(T_o - T_H) + \dot{m_{s-da}}Cp_{da}T_s + \dot{m_{o-da}}Cp_{da}T_o - \dot{m_{r-da}}Cp_{da}T_H)$$

For Temperature, $\%\ Error_{\ steady-state} = 2.65\%$

Dynamic Water vapor energy equation

$$\frac{d(\rho V W h_w)}{dt} = M_{s-da}w_s h_w + M_{o-da}w_o h_o h_w - m_{r-da}w_r h_w$$

$$\frac{dw_H}{dt} = \frac{1}{\rho_w \forall_H}((m_{s-da})w_s + \dot{m_{o-da}}w_o - \dot{m_{r-da}}w_H)$$

For Humidity, $\%\ Error_{\ steady-state} = 4.04\%$

- Equations depict the energy balance in residential spaces, encompassing thermal energy from dry air and water vapor in supply, return, and outdoor air streams.
- Q represents sensible heat transferred into the system via building envelope conduction..

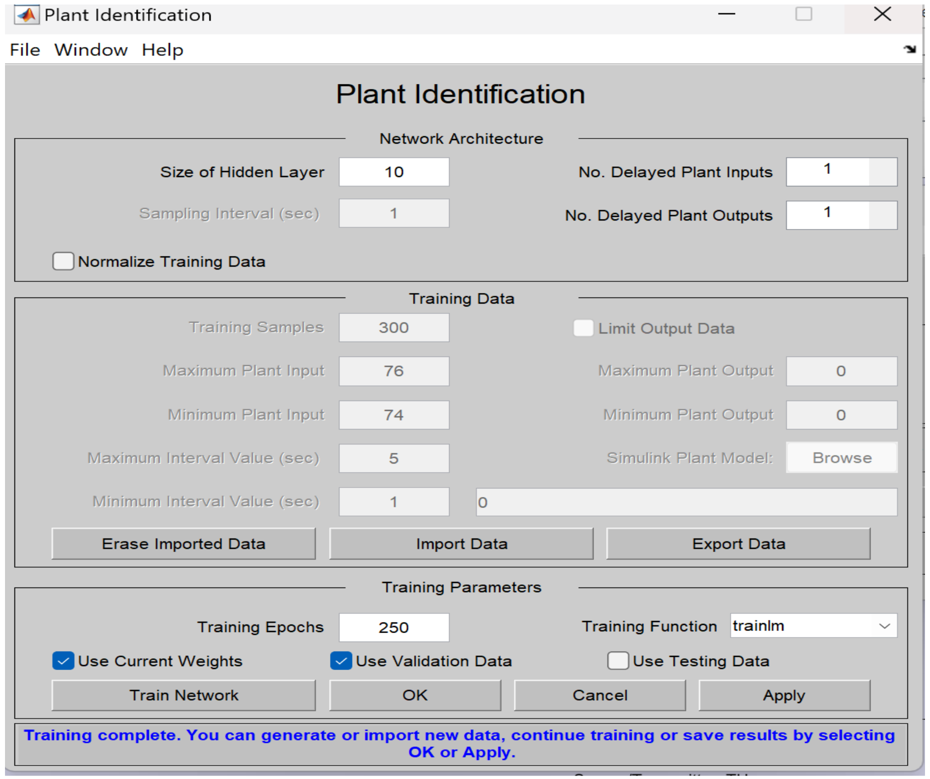
Appendix H – Development of Process ANN Model

A. Plant is trained with three set of data for three different scenarios.

- Firstly, data set for scenario 1^{st} is trained using 10 neurons using "*trailm*" function
- Secondly, trained model with scenario 1^{st} data set again trained with data set for scenario 2^{nd} using 20 neurons
- Finally, the 2^{nd} trained model is again trained with data set for scenario 3^{rd} using 30 neurons

B. Steps for Training and Model Development

- Configure settings for Plant scenario
- Import Data (Generated from ODEs)
- Train Network
- Validation

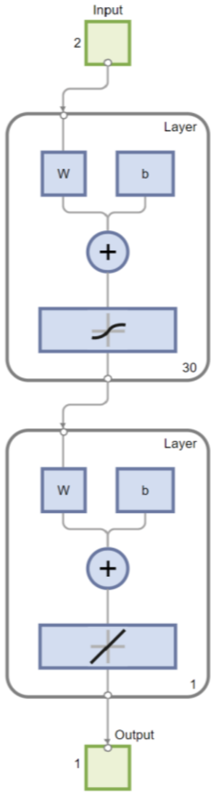


Appendix Fig. 1: Plant Identification configuration

APPENDIX J – OVERALL DIAGRAM AND PERFORMANCE

Training Progress

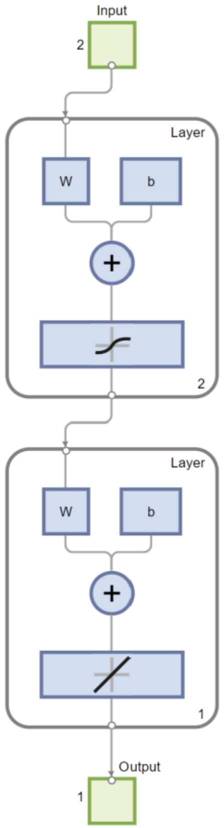
Unit	Initial Value	Stopped Value	Target Value
Epoch	0	9	250
Elapsed Time	-	00:00:00	-
Performance	6.18e+03	0.0991	0
Gradient	7.6e+04	46.8	1e-10
Mu	0.001	0.001	1e+10
Validation Checks	0	6	6



Appendix Fig 2. Neural Network Diagram Temperature (T)

Training Progress

Unit	Initial Value	Stopped Value	Target Value
Epoch	0	4	50
Elapsed Time	-	00:00:00	-
Performance	0.118	1e-23	0
Gradient	0.718	6.96e-13	1e-10
Mu	0.001	1e-07	1e+10
Validation Checks	0	0	6

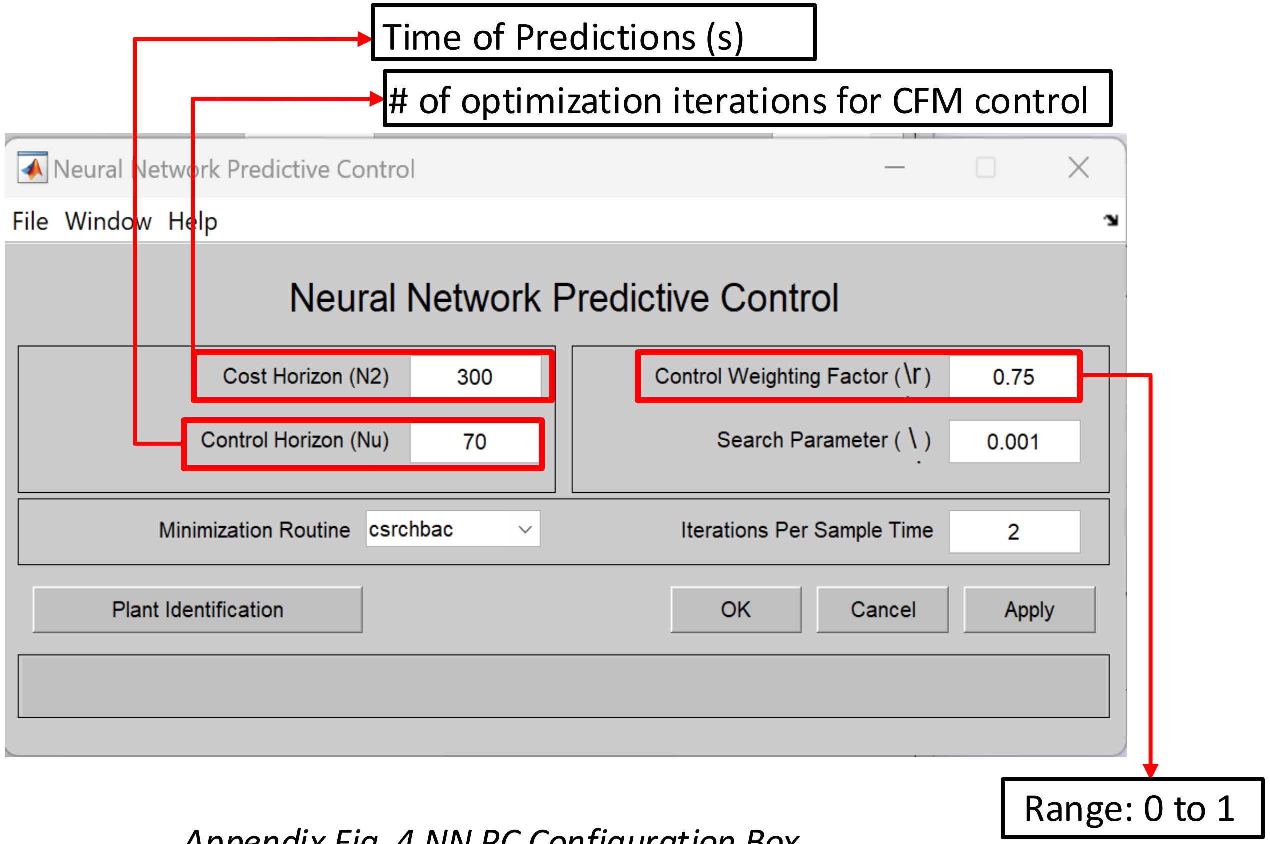


Appendix Fig.3 Neural Network Diagram Humidity (W)

Appendix K – NN PC Configuration

Maximum and Minimum Plant input (Ts) range is based on the EC max capacity for minimum and SHR line to maintain Ts.

- Cost Horizon – Time of predictions
- Control Horizon – Number of times you want to optimize your control (CFM) within cost horizon
- Weight Factor – 0 (Closer to setpoint) – 1 (Energy Savings)



Appendix Fig. 4 NN PC Configuration Box

Appendix L – Evaporative capacity formula (EC)

Type in Ts as a function of CFM.

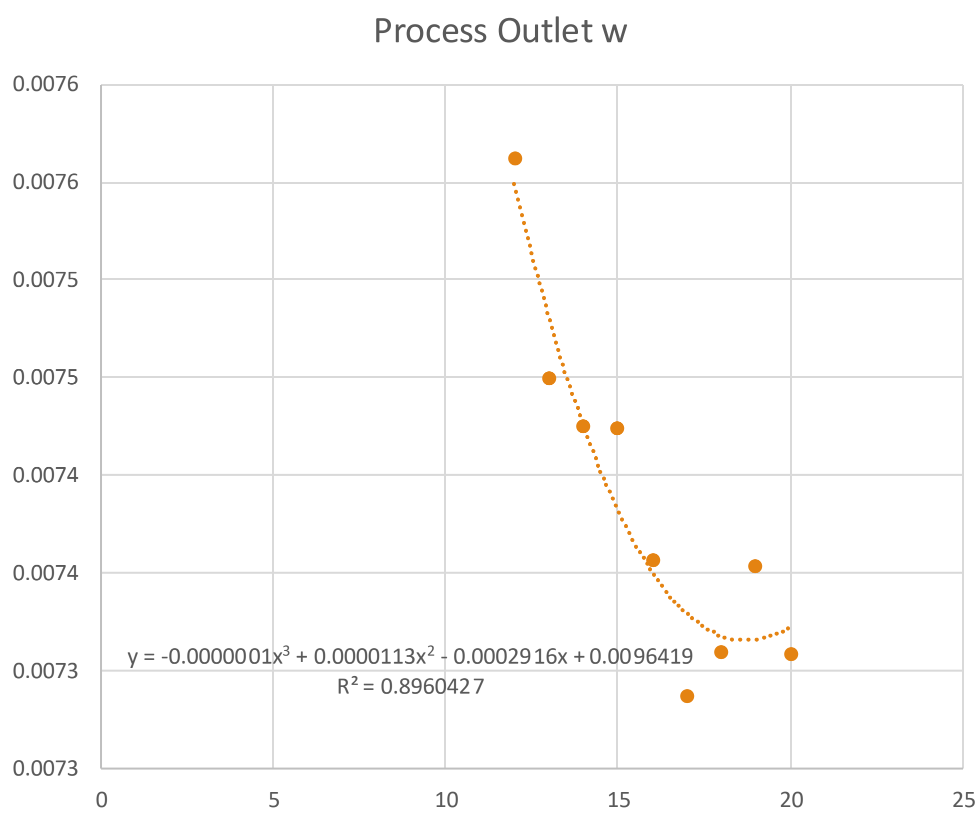
$$T_s = T_{EC,in} - \frac{Q_{cap}}{1.008 * \forall_H}$$

Where, Q_{cap} cooling capacity of evaporative cooler

- $\forall_H$ volume of house

Appendix M – Desiccant wheel humidity removal function (DW)

The equation of the plot relates the humidity entering the system to the rpm of the desiccant wheel



Appendix Fig.5 Process outlet Plot for Humidity

Appendix N – Sensor/ Transmitter Technical Data

Measuring range

Relative Humidity (RH)	0...100 %RH, non-condensing
Temperature (T)	-30...+60 °C (-22...+140 °F)

Outputs

Temperature	0 - 10 V
Relative Humidity (RH)	4 - 20 mA (2-wire)

NB: Ranges of temperature and humidity control from technical data is utilized in calculating the gain of Sensor. Shown in subsequent slide.

Appendix Fig. 6 Sensor Type for Technical Data for Proposed System

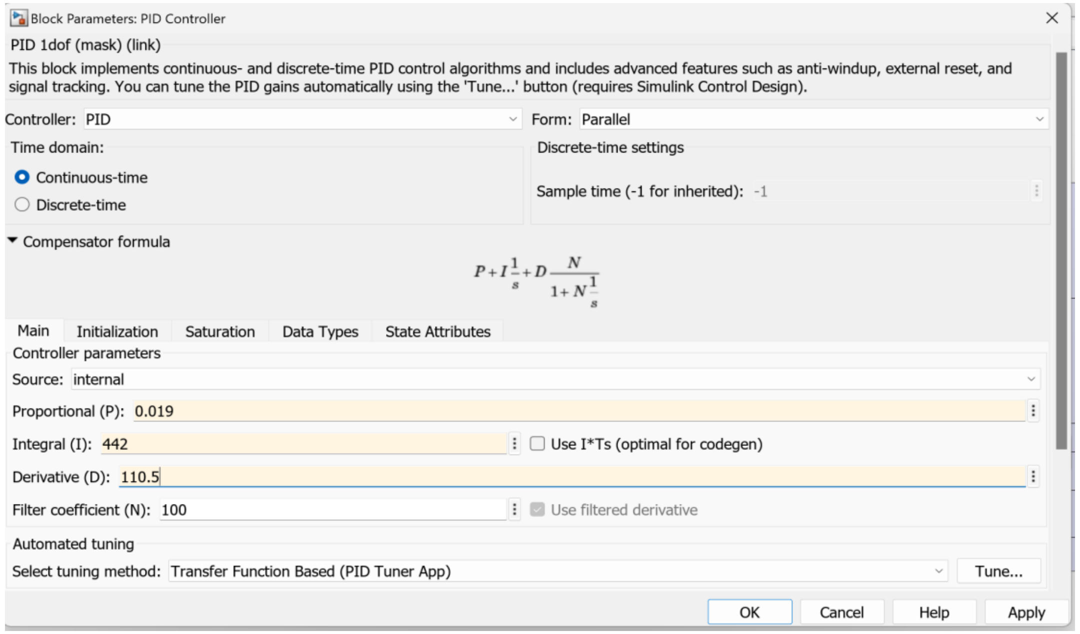
PID Controller tuning

To tune the PID controllers, gains, ti, and td constants were given from open-loop responses using Ziegler Nichols method.

Ziegler–Nichols method[1]

Control Type	K_p	T_i	T_d	K_i	K_d
P	$0.5K_u$	–	–	–	–
PI	$0.45K_u$	$0.8\overline{3}T_u$	–	$0.54K_u/T_u$	–
PD	$0.8K_u$	–	$0.125T_u$	–	$0.10K_uT_u$
classic PID[2]	$0.6K_u$	$0.5T_u$	$0.125T_u$	$1.2K_u/T_u$	$0.075K_uT_u$
Pessen Integral Rule[2]	$0.7K_u$	$0.4T_u$	$0.15T_u$	$1.75K_u/T_u$	$0.105K_uT_u$
some overshoot[2]	$0.3\overline{3}K_u$	$0.50T_u$	$0.3\overline{3}T_u$	$0.6\overline{6}K_u/T_u$	$0.1\overline{1}K_uT_u$
no overshoot[2]	$0.20K_u$	$0.50T_u$	$0.3\overline{3}T_u$	$0.40K_u/T_u$	$0.06\overline{6}K_uT_u$

Appendix Fig. 6 Ziegler-Nichols Tuning parameter table



Appendix Fig. 7 PID Controller tuning parameters input window

Closed-loop using PID control