An Intelligent Fuzzy-PID Controller for Supporting Comfort Microclimate in Smart Homes

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***Abstract*—Addressing the challenge of ensuring a comfortable indoor environment in both commercial and residential buildings through the use of heating, ventilation, and air conditioning (HVAC) systems is a critical issue. This challenge is intricately connected to the development of sophisticated multi-channel controllers to regulate temperature and humidity effectively. This academic discussion initially focuses on the development and examination of a complex, interactive, nonlinear mathematical model that encapsulates the ideal parameters for temperature and humidity to achieve the desired comfort levels. The paper then progresses to explore various methodologies in the design of temperature and humidity control systems. It delves into the traditional Proportional-Integral-Derivative (PID) controllers, a mainstay in the industry, and extends to more advanced iterations. These include the integration of PID controllers with distinct decoupled controllers and the innovative combination of PID controllers with self-adjusting parameters, which are informed by the principles of fuzzy logic. This combination is particularly significant for the processes of heating and humidification. Subsequently, the paper presents the results obtained from simulations conducted on a proposed fuzzy-PID controller using Matlab, a widely used computational tool. These simulations are crucial in evaluating the efficacy of the controller design. Additionally, the paper offers an analysis of experimental data collected over a six-month period. This data is instrumental in assessing the real-world performance of the proposed system, providing valuable insights into its practical applicability and effectiveness in managing indoor climate conditions. In summary, this comprehensive study not only lays the groundwork for an interactive model for climate control but also compares various controller designs, culminating in the proposal and evaluation of an advanced fuzzy-PID controller. This work stands as a significant contribution to the ongoing efforts to enhance indoor climate control in buildings.**

Keywords*—HVAC; Fuzzy logic; energy management; comfort management; smart home

I. Introduction

The quality of the air environment within buildings, governed by a myriad of factors both external (exogenous) and internal (endogenous), is a critical determinant of the conditions under which people live and work, their health, and their overall comfort. The creation of a 'healthy' and comfortable indoor air environment is a complex and costly endeavor, requiring the deployment of advanced, multifunctional engineering systems [1]. The financial implications are significant; for example, eliminating just 1 kW of surplus heat to regulate air temperature within a building can cost between 300 and 600 USD [2]. Traditionally, comfort in indoor environments has been associated with the management of three primary microclimate variables: air temperature (with a precision of ± 1 °C), the temperature of surrounding surfaces, and relative humidity (RH) (with a precision of ± 7%) [3].

Given these factors, the quality and comfort of indoor environments have emerged as topics of growing importance. This has led to the widespread adoption of heating, ventilation, and air conditioning (HVAC) systems in numerous buildings. A key challenge in this area is reducing the energy consumption of HVAC systems while still maintaining an optimal level of comfort – a problem that remains incompletely solved. The International Energy Agency reports that HVAC systems account for approximately 40% of the total energy consumption in residential and commercial buildings [4].

Historically, HVAC systems have been limited in their ability to ensure comprehensive comfort, typically focusing on maintaining environmental conditions within certain thresholds. The optimization of comfort thus relies heavily on the customization of these systems to individual user needs. Conventional approaches have primarily utilized on-off and Proportional Integral Derivative (PID) controllers, designed to minimize the discrepancy between a fixed setpoint and the variable being regulated [5, 6].

Recent research, however, has redefined HVAC systems as multiple-input multiple-output (MIMO) problems, given their operation with interrelated variables to produce a range of output values [7, 8]. These systems are influenced by a variety of uncertain parameters, such as user preferences, occupant activities, and external environmental factors, which can alter their standard operations. Consequently, HVAC control issues are increasingly viewed as multi-criteria tasks, necessitating complex analytical expressions for characterization [9, 10].

While conventional PID controllers offer reasonable solutions, they fall short in fully managing the unpredictability inherent in the dynamics of HVAC systems. These dynamics can be more aptly described using linguistic variables and rules [11, 12]. As an alternative, Fuzzy Logic Controllers (FLC) have gained attention. FLCs do not require mathematical modeling [13] and are capable of handling various criteria, representing the dynamics of HVAC systems based on a knowledge-driven approach. Their efficiency and reduced power consumption, compared to PID controllers, have been demonstrated in recent studies [14, 15].

This paper is structured as follows: Section II reviews related literature, focusing on comfort parameters, control techniques, current challenges in control methods, and future perspectives. Section III outlines the problem statement. Section IV introduces a mathematical model for indoor air temperature and humidity. Section V delves into the design process of intelligent PID controllers for controlling indoor temperature and humidity, explaining proposed techniques for each controlling parameter. Section VI presents simulation results and findings from experiments conducted in our laboratory as part of this study. Section VII and Section VIII presents the discussion and conclusion respectively.

II. Related Works

The Related Works section of this paper provides a comprehensive overview of the existing literature pertaining to the field of heating, ventilation, and air conditioning (HVAC) systems, focusing particularly on the advancement of control techniques and the ongoing quest for optimization of indoor environment quality and comfort. This review is structured to encapsulate the broad spectrum of research conducted in this domain, drawing on a wide range of studies and analyses from diverse sources.

A. Microclimate Control and Comfort Parameters

The domain of microclimate control within architectural spaces necessitates a nuanced understanding of the variables that significantly influence human comfort and well-being. Contemporary research within this sphere has primarily concentrated on identifying and comprehensively understanding the critical elements contributing to human comfort, such as air temperature, humidity, and air quality [17, 18]. These studies underscore the imperative of maintaining precise control over these parameters. This necessity stems not solely from the perspective of ensuring comfort but also from the vantage point of health implications. Inadequate management of air quality, temperature, and humidity has been linked to a range of health complications, thereby highlighting the health-centric dimension of microclimate control [19, 20].

Further extending this discourse, recent scholarly investigations have ventured into examining the subjective aspects of comfort. The subjective perception of comfort, being inherently individualistic and variable, presents a challenge in its quantification and subsequent integration into control systems. These studies have embarked on exploring methodologies to effectively measure and incorporate this subjective element of comfort into the operational frameworks of microclimate control systems [21, 22]. This line of inquiry marks a significant shift from traditional objective measures, paving the way for a more holistic and user-centric approach in the design and management of indoor environmental conditions.

In summation, the body of research in microclimate control and comfort parameters is pivoting towards a more inclusive understanding that encapsulates both the objective and subjective facets of human comfort. This paradigm shift is instrumental in fostering environments that are not only technically sound but also attuned to the nuanced preferences and health requirements of individuals.

B. Energy Efficiency in HVAC Systems

In the realm of Heating, Ventilation, and Air Conditioning (HVAC) systems, a considerable segment of academic research is dedicated to the exploration of energy efficiency. This focus aligns with the broader environmental objectives of promoting sustainability and minimizing carbon emissions. Investigations in this field have been directed towards identifying and implementing strategies to curtail energy consumption in the operation of HVAC systems [23, 24]. Empirical studies have elucidated that enhancements in the energy efficiency of HVAC systems can significantly reduce the overall energy expenditure of buildings. This is particularly pivotal considering the substantial share of energy consumption attributed to HVAC operations [25, 26]. Additionally, the literature indicates a burgeoning interest in adopting progressive approaches towards energy efficiency. These include, but are not limited to, the integration of renewable energy sources and the advancement of smart grid technologies, thereby providing a comprehensive framework for energy optimization in HVAC systems [27, 28]. Such explorations represent a crucial step towards aligning HVAC system operations with the principles of environmental stewardship and sustainable development.

C. Control Techniques in HVAC Systems

The scholarly discourse on Heating, Ventilation, and Air Conditioning (HVAC) systems has been notably enriched by the evolution of control techniques. Central to this discourse is the critical examination of traditional control methodologies, including on-off and Proportional-Integral-Derivative (PID) controllers. These conventional methods have undergone thorough scrutiny, with research primarily concentrated on identifying their limitations and exploring potential enhancements [29, 30]. A pivotal development in this field has been the introduction and subsequent adoption of advanced control techniques, notably Fuzzy Logic Controllers (FLC). Research in this area underscores the superiority of FLCs in managing the intricate and frequently unpredictable dynamics characteristic of HVAC systems [31, 32]. Comparative studies elucidating the distinctions between traditional PID controllers and FLCs have been instrumental in highlighting the strengths of the latter. Notably, FLCs demonstrate enhanced proficiency in dealing with systems that involve multiple variables and are subject to a high degree of uncertainty [33, 34]. This body of research signifies a meaningful shift towards more sophisticated and adaptable control mechanisms in HVAC system management.

D. Modeling and Simulation of HVAC Systems

In the scholarly examination of Heating, Ventilation, and Air Conditioning (HVAC) systems, the aspects of modeling and simulation occupy a position of critical importance. Precise and accurate modeling is fundamental to the comprehensive understanding of HVAC system behavior, which in turn is crucial for the development of efficacious control strategies. The literature in this domain showcases a spectrum of modeling techniques, ranging from the relatively straightforward linear models to more intricate and sophisticated nonlinear and dynamic models [35, 36]. To corroborate the validity and effectiveness of these models, simulation tools like Matlab have been extensively utilized. These tools offer a secure and economically viable avenue for assessing the performance of diverse control strategies across a variety of operational scenarios [37, 38].

Concurrently, the influence of user preferences and external environmental factors on the performance of HVAC systems represents a recurring subject in academic research. Studies have consistently demonstrated that the behaviors and preferences of users can exert a significant impact on the effectiveness of HVAC systems [39, 40]. Moreover, external variables, including meteorological conditions and patterns of building occupancy, are also recognized as playing a pivotal role in determining system performance. Investigations into these factors have been comprehensive and varied [41, 42]. These findings highlight the imperative for HVAC systems to not merely embody technical sophistication but also exhibit adaptability to the dynamic and evolving needs of users, as well as to the fluctuating external environmental conditions. This dual focus on technical advancement and adaptability is crucial for the design and implementation of HVAC systems that are both efficient and responsive to the nuanced requirements of their operational contexts.

E. Challenges and Future Directions

In the concluding segment of the literature review, attention is directed towards the challenges currently confronting the field of Heating, Ventilation, and Air Conditioning (HVAC) systems, alongside prospective avenues for future scholarly inquiry. A primary challenge that emerges from these studies is the incorporation of advanced control techniques into the existing framework of HVAC infrastructure. This integration process poses considerable technical complexities and demands innovative solutions [43]. Furthermore, the literature points to the necessity of developing more comprehensive and intuitive interfaces for the monitoring and control of HVAC systems. Such interfaces are essential to enhance user engagement and system efficiency [44].

Looking forward, the trajectory of research in this domain is anticipated to concentrate on augmenting the adaptability and intelligence of HVAC systems. A significant emphasis is being placed on the integration of cutting-edge technologies such as artificial intelligence (AI) and machine learning (ML). These technologies hold the promise of revolutionizing HVAC systems, making them more responsive and efficient [45]. The integration of AI and ML is expected to enable HVAC systems to learn from and adapt to changing environmental conditions and user preferences, thereby optimizing performance and energy efficiency.

In summation, the corpus of literature surrounding HVAC systems is comprehensive and multifaceted, encompassing a diverse range of topics from basic considerations of microclimate control and comfort parameters to the exploration of advanced control methodologies and the identification of future research directions. This extensive body of work lays a robust foundation for ongoing studies and highlights the imperative for continued research and development in this field. The ultimate goal is to realize HVAC systems that are not only more efficient and adaptable but also more user-friendly, thereby aligning with the evolving needs and expectations of contemporary society.

III. PROBLEM STATEMENT

This research endeavor is primarily focused on devising control strategies that amalgamate traditional and intelligent control technologies to optimize indoor environment quality. This includes the regulation of indoor air temperature and humidity, achieved through a blend of computational modeling and empirical investigation. The overarching objective of this strategy is to explore and demonstrate avenues for enhancing the comfort of occupants within built environments. To this end, the development and analysis of three distinct controllers are undertaken. These controllers are designed to assess the efficacy of newly proposed control mechanisms in managing indoor environmental quality. Additionally, this study seeks to evaluate the feasibility and effectiveness of employing intricate control strategies that are an integration of various control techniques.

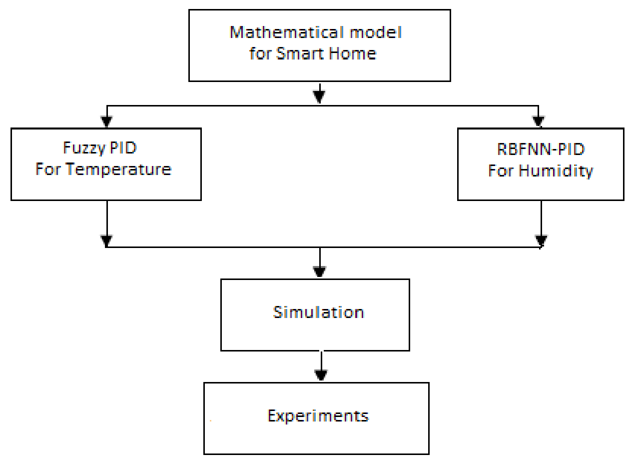

Fig. 1. Stages of designing an intelligent PID control system.

The methodology and progression of this research are methodically outlined in Fig. 1. This breakdown delineates the various stages of the study, providing a clear and structured roadmap for the investigation. Each phase of the research is designed to build upon the findings of the preceding stages, thereby ensuring a comprehensive and systematic exploration of the control strategies under consideration. This approach allows for a thorough examination of the potential and limitations of both conventional and intelligent control technologies in the context of indoor environment quality control, with a specific focus on enhancing occupant comfort in built environments.

IV. MATHEMATICAL MODEL

This study investigates a typical room outfitted with a foundational Heating, Ventilation, and Air Conditioning (HVAC) system, as depicted in Fig. 2. The system is equipped with a heater using hot/cold water and a humidifier employing steam. The process begins with the modulation of the mixed air temperature post-filtration, wherein the external air is either heated or cooled via a heating/cooling coil. Following this, the external air may undergo humidification through a steam humidifier before being circulated into the room by a supply fan. Concurrently, exhaust air is expelled from the room by a return fan.

A critical component of this system is the heating/cooling coil, which imparts thermal-humid energy, denoted as P, to the indoor air. This energy transfer is modulated by varying the flow rate of hot/cold water (Fp) through the Hot Water Return/Cooling Heat Recovery (HWR/CHR) control valve. Similarly, the steam humidifier contributes thermal-humid energy, represented as Q, to the indoor air by adjusting the steam flow rate (Fq) via the control steam valve. The system's temperature and humidity are regulated by manipulating the positions of the hot/cold water and steam valves, thereby altering the flow rates Fp and Fq in accordance with specific equations [46].

The indoor temperature is influenced by multiple factors, including the initial indoor microclimate air temperature, outdoor temperature, the volume of the premises, the efficiency of the heater or air conditioner, and the heat loss through the walls. Based on the principles of energy conservation, the indoor air temperature can be mathematically expressed, taking into account these variables and their interplay as depicted in Fig. 2. This expression is central to understanding the dynamics of indoor temperature regulation and forms the basis for further exploration and analysis in this study.

$$\rho_a V_{indoor} C_p \frac{dT_{indoor}(\tau)}{d\tau} = a_p F_p(t) - U_w A_w \left[T_{indoor}(\tau) - T_{outdoor}(\tau)\right] \quad (1)$$

Here, ρ_a air density, V_{indoor} volume of air into the room, C_p heat capacity of air, T_{indoor} indoor air temperature, τ time, a_p channel coefficient, F_p water flowrate into heating/cooling system, $T_{outdoor}$ outdoor air temperature, A_w square of the wall, U_w overall heat transfer coefficient for the wall.

To simplify Laplace transforms as presented in Eq. (3), the process typically involves converting the time-domain equation into its corresponding s-domain representation. This conversion facilitates the analysis of systems, particularly in the context of control systems and differential equations. The Laplace transform essentially converts differential equations, which can be complex to solve in the time domain, into algebraic equations in the s-domain, which are simpler to manipulate and solve.

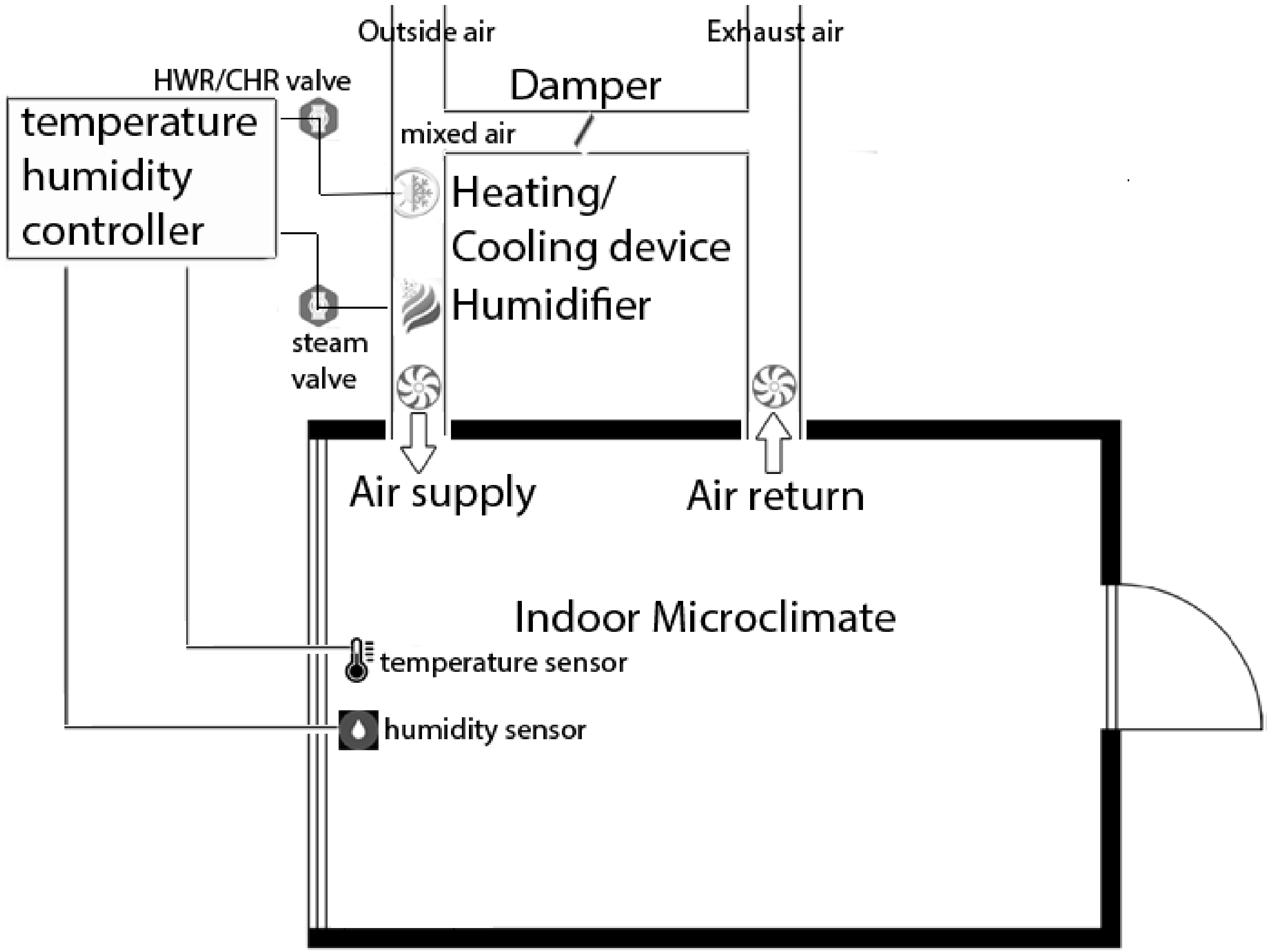

Fig. 2. Schematic diagram of indoor air temperature and humidity control processes in HVAC system.

In the context of the specific Eq. (1) you're referring to, the Laplace transform would take each term of the equation and convert it into its Laplace form. This involves identifying the Laplace transform of each component of the equation – for instance, functions of time, derivatives, and integrals – and representing them in terms of 's', which is the complex frequency parameter in the Laplace domain.

$$\left[\frac{\rho_a V_{indoor} C_p}{U_W A_W} s + 1\right] \cdot T_{indoor}(s) = \frac{a_P}{U_W A_W} F_P(s) + T_{outdoor}(s) \tag{2}$$

Under the assumption that the indoor temperature is not influenced by the outdoor temperature and considering the time delay inherent in the heat transfer process within an indoor environment, the simplification of Eq. (4) can be approached by focusing on the internal dynamics of the system while disregarding external thermal influences.

$$G_{11} = \frac{T_p(s)}{F_p(s)} = \frac{k_{tp} e^{-q_{tp} s}}{t_{tp} s + 1} \tag{3}$$

When considering the relationship between temperature and humidity in an indoor environment, it's essential to acknowledge that changes in humidity can significantly affect air temperature. The operation of a humidifier, by adding moisture to the air, can influence the thermal characteristics of the space. This is due to the latent heat exchange involved in the process of humidification, which can either absorb or release heat, thereby affecting the overall air temperature.

Incorporating the effect of the humidifier on the temperature, typically represented by the temperature Tq affected by the humidification process, the indoor air temperature can be modeled taking into account both the direct heating or cooling effect (through HVAC systems) and the indirect effect of humidification. The relationship can be expressed in a combined form where the temperature equation accounts for the additional variable Tq.

The modified equation would typically include terms representing the heat added or removed by the HVAC system and the change in enthalpy due to humidification. The equation might take a form similar to:

$$G_{12} = \frac{T_q(s)}{F_q(s)} = \frac{k_{tq} e^{-q_{tq} s}}{t_{tq} s + 1} \tag{4}$$

Where, G_{12} Laplace transfer function, F_q flowrate of steam, $t_{tq} = \frac{V_{indoor}}{f_a}$, $k_{tq} = \frac{a_q a_t}{f_a r_a E_p}$.

V. Fuzzy Rules for HVAC Control

In the pursuit of maintaining internal thermal comfort within a specified environment, a controller equipped with fuzzy inference capabilities has been developed. This controller is tasked with calculating the necessary power to sustain the desired thermal conditions. The operational mechanism of this fuzzy controller is based on the inputs of error and error rate of change, which are pivotal in guiding its decision-making process.

The concept of 'error' in this context refers to the deviation between the desired temperature setpoint and the actual temperature observed within the environment, represented as e (measured in degrees Celsius, °C). This error is a critical factor in determining the necessary adjustments required to achieve thermal comfort. Additionally, the controller considers the rate of change of this error over time, which is essentially the first derivative of the temperature variation within a given computational cycle. This rate of change is measured in °C/min and provides insight into the dynamic behavior of the temperature within the environment [47].

The primary challenge addressed by this controller is the accurate determination of the temperature output that should be relayed to the digital-to-analog converter regulator. This regulator then executes the necessary adjustments to align the actual temperature with the desired setpoint. The input variables for this regulator include the aforementioned error e and the rate of change of this error. By leveraging these inputs, the fuzzy inference controller can make nuanced decisions that account for both the current state and the trajectory of the temperature, thereby ensuring efficient and responsive control for maintaining internal thermal comfort.

$$\Delta e = T_{desired}(t) - T_{current}(t) \tag{5}$$

where, $T_{desired}(t)$, $T_{current}(t)$ are the desired and current temperatures in °C and t is the time in minutes.

The rate of temperature change in a given environment, particularly when cooling or heating is involved, is intrinsically linked to the magnitude of the temperature difference between the desired setpoint and the current temperature. This relationship is a fundamental principle in thermodynamics and heating, ventilation, and air conditioning (HVAC) system dynamics.

Mathematically, the rate of temperature change can be expressed through a formula that incorporates the temperature difference as a key variable. The formula typically takes into account not only the temperature difference but also the efficiency and capacity of the heating or cooling system, the thermal properties of the space (like insulation and volume), and external factors such as ambient temperature.

The rate of temperature change (ΔT/Δt), where ΔT is the temperature difference and Δt is the time interval, can be represented as:

$$\Delta e = \frac{e(t_1) - e(t_2)}{t_1 - t_2} \tag{6}$$

In the development of a fuzzy logic controller for temperature regulation, the concept of linguistic fuzzy variables becomes paramount. These variables allow for the characterization of the system's state in a manner that is akin to human reasoning, which is especially useful in systems where precision and complex calculations are less feasible or desirable. In this context, the linguistic fuzzy variables are designed to describe the temperature difference (e) and the rate of temperature change.

The construction of membership functions for these variables is a critical step in the fuzzy logic design process. Membership functions define how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. For this controller, two distinct membership functions are formulated:

Temperature Difference (e): This function maps the temperature difference (e) within the range of -6 to +6 °C. The linguistic identifiers for this membership function include:

Large Positive Deviation (LPD)

Average Positive Deviation (APD)

Small Positive Deviation (SPD)

Zero Deviation (Z)

Small Negative Deviation (SND)

Average Negative Deviation (AND)

Large Negative Deviation (LND)

Rate of Temperature Change: This function represents the rate of temperature change within the range of -6 to +6 °C/min. The same linguistic identifiers (LPD, APD, SPD, Z, SND, AND, LND) are used to describe the rate of change.

These membership functions, as visualized in Fig. 3 for the temperature difference and Fig. 3 for the rate of temperature change, enable the fuzzy logic controller to interpret and respond to various states of the indoor environment. The output parameter value, which is the result of the joint effect of these two membership functions, is determined by the control logic programmed into the fuzzy logic controller. This logic dictates how the controller responds to different combinations of temperature difference and rate of change, guiding the adjustments needed to achieve and maintain the target indoor temperature.

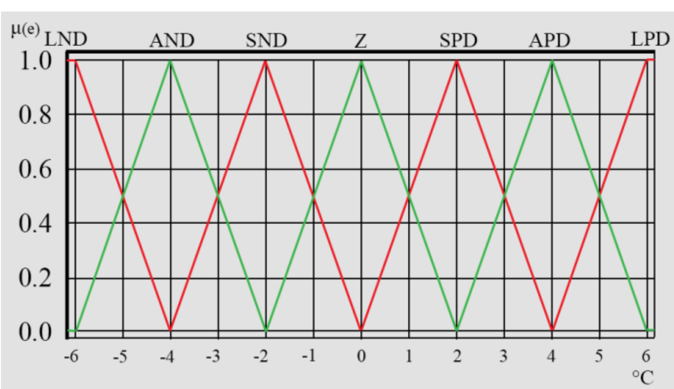

Fig. 3. Linguistic membership functions by the input parameter.

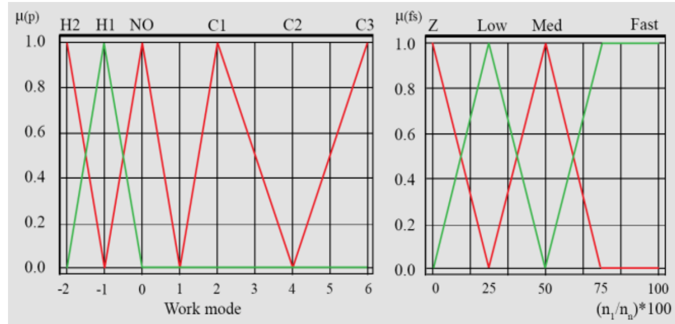

Fig. 4. Linguistic membership functions by output parameter.

Utilizing the established membership functions, as delineated in Fig. 4, the optimal operational mode for the heating and cooling systems within an indoor environment can be determined through fuzzy logic control. This control strategy employs a set of fuzzy variables, each with specific identifiers to represent different levels of heating and cooling required. These variables and their respective identifiers are:

Utilizing the established membership functions, as delineated in Fig. 4, the optimal operational mode for the heating and cooling systems within an indoor environment can be determined through fuzzy logic control. This control strategy employs a set of fuzzy variables, each with specific identifiers to represent different levels of heating and cooling required. These variables and their respective identifiers are:

For Cooling:

Strong Cooling (C3)

Average Cooling (C2)

Slight Cooling (C1)

For Heating:

Heating 1 (H1)

Heating 2 (H2)

For Neutral State:

Without Changes (NO)

In a similar fashion, the control of the fan rotation speed is computed based on a rule base, as visualized in Fig. 4. The fuzzy variables for fan speed are identified as:

High (Fast)

Normal (Med)

Low (Low)

Zero (Z)

The output membership function, represented in Fig. 4, illustrates the processing rule employed in the fuzzy logic system. This rule aggregates the response signals to generate a comprehensive output command. The chosen function in this study is designed to provide an output encompassing two heating levels (H1, H2), three cooling levels (C1, C2, C3), and a normative level (NO). This approach allows for a nuanced response to varying thermal conditions, enabling the system to adaptively modulate the heating or cooling levels, as well as the fan speed, in accordance with the real-time requirements of the indoor environment.

The flexibility of the fuzzy logic control system lies in its ability to interpolate between these defined levels, potentially envisaging scenarios where additional heating or cooling levels could be implemented. This could involve settings that exceed the defined parameters of H2 for extra heating or provide cooling options that are more intense than the levels of C2 and C1, thus catering to a wide range of environmental conditions and occupant comfort preferences.

Table I in the study delineates the application of linguistic variables, which are derived from the process of fuzzification applied to the response signal. This fuzzification process is significantly guided by operator intuition, a crucial aspect in the fuzzy logic control system. The linguistic variables, as defined and used in the system, encapsulate the varying degrees of response required for temperature regulation within the indoor environment.

TABLE I. LINGUISTIC MEMBERSHIP FUNCTIONS BY OUTPUT PARAMETER

		Temperature difference (e)						
		LND	***AND***	***SND***	***Z***	***SPD***	***APD***	***LPD***
Rate of temperature change	**LND**	C3	C3	C2	C1	NO	NO	H1
		Fast	Fast	Med	Slow	Z	Z	Med
	AND	C3	C2	C2	C1	NO	NO	H1
		Fast	Med	Med	Slow	Z	Z	Med
	SND	C3	C2	C1	C1	NO	NO	H1
		Fast	Med	Slow	Slow	Z	Z	Med
	Z	C2	C1	C1	NO	NO	H1	H1
		Med	Slow	Slow	Z	Z	Med	Med
	SPD	C1	C1	NO	NO	H1	H1	H2
		Slow	Slow	Z	Z	Med	Med	Fast
	APD	C1	C1	NO	NO	H1	H2	H2
		Slow	Slow	Z	Z	Med	Fast	Fast
	LPD	C1	C1	NO	NO	H2	H2	H2
		Slow	Slow	Z	Z	Fast	Fast	Fast

e	+ very cold	conditioner
	- very hot	
Δe	+ heat consumption	ventilator
	- cold consumption (heat output)	

VI. EXPERIMENTAL RESULTS

In this segment, we present the modeling and simulation results for a fuzzy Proportional-Integral-Derivative (PID) controller, specifically applied to the task of temperature regulation. The scenario begins with the assumption that the initial temperature within a room is not at an optimal level, thus necessitating adjustment. Upon setting a target temperature, the controller initiates its operation to achieve this desired thermal state. For the purpose of simulating this process, a reference input signal, indicative of the temperature difference to be addressed, is employed. Let us consider a scenario where the temperature difference between the internal environment and the external medium is set at 5 °C. Consequently, a step signal, denoted as r(k)=5, is introduced at the initiation of the simulation (time = 0 t=0).

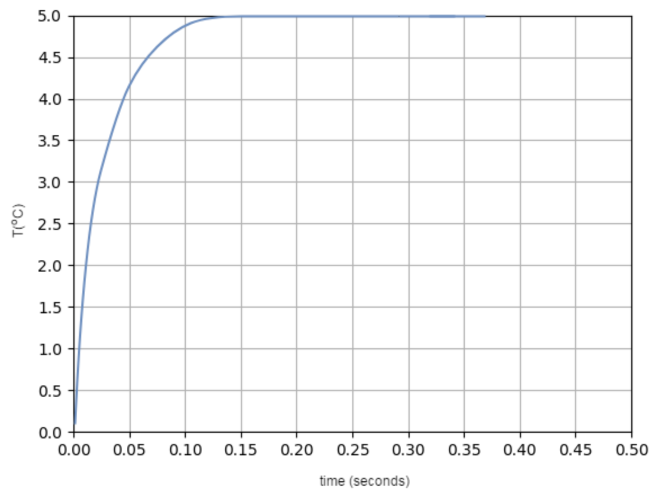

Fig. 5. System output response to step input.

The resultant simulation output of the temperature control system is depicted in Fig. 5. Analyzing the figure, we observe key performance metrics such as the time constant τ=0.033 seconds) and the settling time (t=0.092 seconds). These metrics are indicative of the controller's responsiveness to the input signal. Notably, the control system exhibits a rapid reaction time, characterized by a high rate of increase in response to the step change in temperature.

Additionally, the response dynamics of the system demonstrate the absence of overshoot, which is a desirable attribute in control systems, indicating precision and stability in reaching the target state without exceeding it. Moreover, the steady-state error is observed to be zero at the point where the control process stabilizes. This absence of steady-state error signifies that the proposed fuzzy PID control system effectively attains the desired temperature without deviation, thereby exemplifying its excellent performance. The system not only responds swiftly but also maintains control accuracy and stability, ensuring that the desired room temperature is achieved efficiently and reliably.

In the pursuit of maintaining internal thermal comfort within a specified environment, a controller equipped with fuzzy. Upon integrating these linguistic variables with the output membership function and subsequent de-fuzzification process, a distinct and actionable control signal is generated. This signal is pivotal in the fuzzy logic control system as it dictates the specific control actions to be undertaken by the heating and cooling systems. The control signal, in essence, represents the required level of heating or cooling, quantified in a range that typically includes values such as [−2, −1, 0, 1, 2, 3, ...]. These values correspond to the degrees of heating or cooling necessary to maintain or achieve the desired indoor temperature.

For instance, negative values (e.g., -2, -1) might indicate the need for cooling at various intensities, while positive values (e.g., 1, 2) suggest varying levels of heating. A zero value (0) would imply that no change is needed, maintaining the current state. The higher the absolute value, the more intense the heating or cooling action required.

The transformation of fuzzy inputs into a clear and quantifiable control signal through de-fuzzification is a crucial step, enabling the practical application of fuzzy logic theory in real-world control systems. This process ensures that the inherently vague and subjective nature of linguistic variables is translated into precise control actions, effectively bridging the gap between human-like reasoning and mechanical system control.

This figure elucidates how the controller's command, formulated based on the output data, is calculated and subsequently dispatched to the requisite device. This command is integral to modifying the air temperature within the room, showcasing the controller's active role in environmental regulation.

Further examination is presented in Fig. 6, which delineates the automatic adjustment process of the PID parameters. From these observations, it can be conclusively stated that the fuzzy PID control methodology effectively modifies the traditional PID controller parameters. This adaptability optimizes the control performance, ensuring that the system is responsive and stable, thereby achieving the desired environmental conditions with enhanced precision.

Fig. 6 presents a graphical depiction of the variations in carbon dioxide (CO2) levels over the course of a single working day in January 2021. This visualization provides insightful data on how human presence and activities in a workplace environment impact indoor air quality, particularly concerning CO2 concentration.

At the commencement of the working day, the CO2 concentration was observed to be low. However, a notable increase in the level of CO2 was recorded around 9:00 AM, corresponding with the arrival of employees at the workplace. This sharp rise in CO2 levels is attributable to the increased number of people, and hence, respiration rates within the enclosed space.

Subsequently, the efficiency of the air quality control system is evidenced as the CO2 levels are reduced to below 1000 parts per million (ppm). This reduction signifies the effective functioning of the ventilation or air purification system in managing and maintaining optimal air quality despite the increased occupancy.

An interesting variation is observed during the lunch hour, starting from 13:00 and lasting until 14:00. During this period, there was a discernible decrease in CO2 concentration to approximately 600 ppm. This reduction can be attributed to the opening of windows, allowing for enhanced natural ventilation and dilution of indoor CO2 levels. Post-lunch, as employees resumed their activities, the CO2 concentration experienced an immediate upsurge, eventually stabilizing at a comparatively steady level. This pattern suggests a consistent occupancy and activity level in the afternoon hours.

Finally, after 18:00, coinciding with the end of the workday and the departure of the employees, a decrease in CO2 levels was again observed. This trend aligns with the reduced human presence in the building, leading to lower respiration rates and thus, lower CO2 emission within the indoor environment. This diurnal pattern in CO2 levels highlights the direct correlation between human occupancy and indoor air quality, as well as the critical role of effective air quality management systems in maintaining a healthy indoor environment.

Monitoring the level of CO2 in indoor environments is crucial, distinctly different from the regulation of relative humidity and temperature, which are typically maintained within a specific range. The dynamics of CO2 concentration, particularly in scenarios where the air conditioning system is operational or when natural ventilation is enabled, are critical for indoor air quality (IAQ) management.

When the air conditioning is active or when the area is naturally ventilated (referred to as the air conditioning region being 'open' or 'free'), there is a noticeable decrease in CO2 levels within the room. This effect brings the CO2 concentration down to a lower, more desirable setting. In such scenarios, the CO2 levels inside the room fluctuate within a comparative range. However, it is important to note that standard deviation, a common statistical measure, may not adequately represent the effectiveness of air quality rate control strategies in managing CO2 levels.

Consequently, the internal temperature is often utilized as a more reliable parameter for assessing the performance of IAQ controllers. Fig. 7 in the study highlights the maximum monthly internal CO2 concentration observed. The findings indicate that the peak daily CO2 concentration does not exceed 1100 parts per million (ppm). This concentration level, while being the highest observed, is still within a range that is considered not harmful to human health and does not persist for prolonged durations.

Such insights are crucial in understanding the efficacy of IAQ control systems in maintaining CO2 concentrations at safe levels, ensuring a healthy indoor environment. This focus on CO2 levels, alongside temperature and humidity, forms a comprehensive approach to IAQ management, safeguarding both comfort and health within indoor spaces.

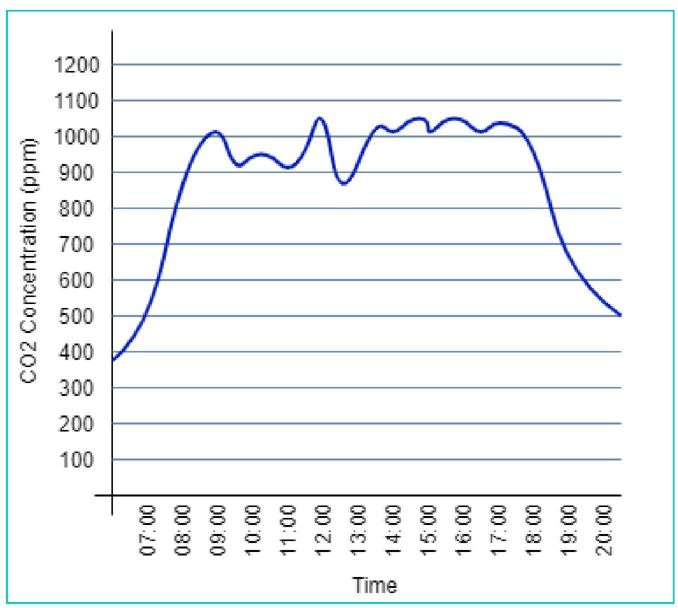

Fig. 6. Indoor CO2 concentration level.

Fig. 7. Indoor CO2 concentration level for six months.

VII. Discussion

In the Discussion section of this paper, we critically examine the findings from our study on the implementation of a fuzzy PID controller for indoor climate control, with a particular focus on temperature regulation and CO2 level monitoring.

Temperature Control and CO2 Monitoring: Our research underscores the significance of precise temperature control and effective CO2 monitoring in indoor environments [48]. The implementation of a fuzzy PID controller demonstrated substantial efficacy in maintaining the desired temperature levels. This outcome is particularly noteworthy given the dynamic nature of indoor environments, where temperature can be influenced by various factors such as human occupancy, external weather conditions, and heating or cooling systems [49]. The fuzzy logic aspect of the controller, with its ability to handle imprecise inputs, proved crucial in adapting to these dynamic conditions.

Moreover, the CO2 level monitoring presents an additional layer of complexity. Unlike temperature and humidity, which are regulated within a defined range, CO2 levels require continuous monitoring to ensure they remain within safe limits. The study's findings reveal that the integration of ventilation systems or natural air flow significantly impacts the reduction of CO2 levels, emphasizing the importance of adequate ventilation in indoor spaces for air quality management [50].

Performance of the Fuzzy PID Controller: The fuzzy PID controller's performance, particularly in the context of its rapid response and stability, is a highlight of this study. The controller's swift adaptation to changes in temperature and its ability to stabilize the indoor climate without overshooting the desired parameters underscore its efficiency [51]. The automatic tuning of PID parameters (kp, ki, and kd) according to fuzzy logic control rules further enhances the system's responsiveness and accuracy. This adaptability is crucial in scenarios where indoor conditions fluctuate frequently.

Limitations and Future Work: Despite the positive outcomes, there are limitations to this study that open avenues for future research. The study primarily focuses on a controlled environment, and extending these findings to more varied and complex real-world scenarios would be beneficial [52]. Further research could explore the integration of additional environmental factors, such as humidity levels and air pollutants, into the control system for a more comprehensive approach to indoor climate control.

Additionally, the study's reliance on specific models and simulation tools may limit its generalizability. Future research could look into the application of the fuzzy PID controller across different models and simulation environments to validate its effectiveness further.

Implications for Indoor Air Quality (IAQ) Management: The findings have significant implications for IAQ management. Maintaining optimal levels of temperature and CO2 is not only essential for comfort but also for health. Elevated CO2 levels can lead to decreased cognitive function and increased health risks. Therefore, the ability of the fuzzy PID controller to effectively manage these parameters is crucial [53]. The insights gained from this study could inform the design and implementation of HVAC systems in various settings, from residential buildings to office spaces and public facilities.

Environmental and Energy Considerations: Environmental sustainability and energy efficiency are other critical aspects highlighted by this research. The intelligent control of HVAC systems, as demonstrated by the fuzzy PID controller, can contribute to energy conservation by optimizing the operation of heating and cooling systems. This optimization not only reduces energy consumption but also minimizes the environmental footprint of buildings.

The study presents a significant contribution to the field of HVAC system control, particularly in the areas of temperature regulation and CO2 monitoring. The implementation of a fuzzy PID controller demonstrates a promising approach to managing indoor climate conditions, balancing comfort, health, and energy efficiency. Future research expanding on these findings and addressing the identified limitations could pave the way for more sophisticated and environmentally sustainable indoor climate control solutions.

VIII. Conclusion

In conclusion, this research paper has made a significant contribution to the field of indoor climate control by exploring the efficacy of a fuzzy Proportional-Integral-Derivative (PID) controller in regulating temperature and monitoring carbon dioxide (CO2) levels in indoor environments. The findings of this study underscore the importance of precise environmental control in indoor settings, not only for occupant comfort but also for health and energy efficiency. The implementation of the fuzzy PID controller has demonstrated a commendable level of adaptability and accuracy in maintaining desired temperature levels, even in the face of varying indoor conditions and external influences. The integration of fuzzy logic with traditional PID control has enhanced the system's ability to handle ambiguous and fluctuating data, a common characteristic in real-world environments. Furthermore, the focus on CO2 level monitoring, a critical component of indoor air quality, highlights the necessity of continuous surveillance of environmental parameters beyond temperature and humidity.

A key takeaway from this research is the controller's capability to rapidly respond to changes in the indoor environment and stabilize the conditions without overshooting the set parameters. This responsiveness is crucial in ensuring a consistent and comfortable indoor climate. Additionally, the study's insights into the automatic tuning of PID parameters based on fuzzy logic control rules contribute to the broader understanding of intelligent control systems in HVAC applications. Despite its successes, the study acknowledges the need for further research in more diverse and complex settings to validate the generalizability of the findings. Future investigations could also delve into the integration of other environmental factors and explore the potential for advanced predictive control mechanisms.

In essence, this research provides a valuable framework for the development of sophisticated and efficient climate control systems, offering significant benefits in terms of occupant well-being, environmental sustainability, and energy conservation. The implementation of such intelligent control systems is poised to play a pivotal role in the evolution of smart building technologies and the advancement of indoor environmental quality.

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