Frequency response-based optimization of PID controllers for enhanced fluid control system performance

Herri Trisna Frianto[1,2], Syahrul Humaidi[1], Kerista Tarigan[1], Dadan Ramdan[3], Doli Bonardo[4]
[1]Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara, Medan, Indonesia
[2]Department of Electrical Engineering, Medan State Polytechnic, Medan, Indonesia
[3]Department of Electrical Engineering, Faculty of Engineering, Universitas Medan Area, Medan, Indonesia
[4]Department of Electrical Engineering, Faculty of Maritime Engineering and Technology, Universitas Maritim Raja Ali Haji, Tanjungpinang, Indonesia

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ABSTRACT

Temperature and viscosity variations are known to affect the performance of proportional-integral-derivative (PID) controllers in fluid systems. However, there exist gaps in research relative to the thermal effects on the performance of PID based fluid systems. PID controllers are also utilized for fluid control to maintain stability and improve performance. This study aims to explore the influence of temperature and viscosity variations through frequency response analysis for the first time in this regard. Utilizing a controlled experimental setup, gain and phase values were measured across different temperature points. Bode and Nyquist plots were generated to observe system behavior, stability, and response to changes in temperature and fluid viscosity. The results show a clear inverse relationship between temperature and gain, with a notable phase lag increase as temperature rises. At 25 °C, the gain was measured at 15.83 dB with a phase of -52.63°, which gradually reduced to a gain of 13 dB and a phase of -61.53° at 80 °C. The Nyquist analysis revealed stable operation within this temperature range, but the shift in response indicates increased system vulnerability as viscosity decreases with rising temperature. The derived linear equations effectively model the gain-phase relationship, with an R^2 of 0.9985, suggesting a highly accurate fit. Overall, the study concludes that temperature-induced viscosity changes significantly impact PID-controlled fluid systems, emphasizing the need for adaptive control strategies in fluctuating environments.

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Corresponding Author:

Syahrul Humaidi
Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara
Bioteknologi Street No. 1, Medan 20155, Indonesia
Email: syahrul1@usu.ac.id

1. INTRODUCTION

The precise control of fluid flow and pressure is paramount in a wide array of applications, spanning from domestic and industrial practice [1], [2]. Recently, proportional-integral-derivative (PID) controllers have found broad application in maintaining control of fluid flow and pressure and, as a consequence, the performance of such systems [3]-[5]. However, plumbing systems can be affected by non-linear parameters such as alteration in the fluid's viscosity [6], [7] and temperature [8], [9], which classical PID controllers can't handle appropriately. These non-linearities can lead to significant variations in system performance, especially when the environmental conditions fluctuate. Modern industrial processes increasingly demand control systems capable of maintaining stability and optimal performance across diverse and dynamic operating conditions. In many fluid control systems, the non-linear behavior arises from variations in physical properties such as viscosity, density, and pressure, all of which can fluctuate significantly due to environmental factors like temperature changes [10]. For instance, in industrial applications where fluids are used in manufacturing processes, even slight deviations in temperature can alter the fluid's viscosity, leading to erratic system responses [11]. This unpredictability challenges traditional PID controllers, which are typically designed for linear systems operating within fixed parameters [12]. As a result, the system may experience oscillations, overshooting, or even instability when faced with such conditions [12], [13].

The influence of temperature on fluid dynamics is particularly critical because it affects the Reynolds number, which in turn changes the flow regime from laminar to turbulent [14], [15], further complicating the control process [16]. In plumbing systems, this shift can cause abrupt pressure fluctuations [17], making it difficult for standard PID controllers to maintain set points reliably [18]. This issue becomes more pronounced in large-scale industrial systems where maintaining precise control over flow and pressure is essential for safety, efficiency, and energy consumption [19]. Addressing these challenges requires advanced control strategies that can adapt to or mitigate the effects of such non-linearities without significantly increasing system complexity or computational load. Given the increasing demand for highly efficient and adaptable control systems in both household and industrial applications, exploring the integration of environmental factors such as temperature into PID control strategies is crucial. Developing a robust PID controller capable of handling non-linear behavior ensures not only improved system stability but also reduces the likelihood of operational failures [20], enhances energy efficiency [20], and minimizes maintenance costs.

Numerous studies have investigated the implementation of PID controllers in various fluid systems. Traditional approaches focused on linear system models, where PID controllers were tuned to achieve optimal performance within a narrow range of operating conditions [21]. The Ziegler-Nichols method, for instance, has been a popular technique for tuning PID controllers, delivering satisfactory results in many applications [22]. However, several studies have highlighted limitations in handling non-linearities, particularly under conditions of variable fluid properties such as viscosity and temperature. For example, a recent review has explained that PID controllers tuned for ideal conditions often experience degraded performance when applied to systems with significant environmental variations, leading to instability and inefficiency [23]. While a few researchers have addressed these limitations by introducing adaptive or robust PID control strategies, which adjust the control parameters dynamically based on real-time system feedback [24], [25], these methods require complex implementations and higher computational resources. Despite these advancements, there is still a gap in the literature regarding PID controllers that can effectively handle non-linear behavior while maintaining simplicity and low computational cost.

This research, therefore, concerns the analysis of the performance of a fluid control system which employs a PID controller under fluctuating temperature conditions while modeling the non-linearity owing to the change of a fluid's viscosity. The primary problem this study seeks to solve is the degradation of PID controller performance and system stability in fluid control systems subjected to significant temperature and viscosity variations, which are common in real-world industrial and domestic environments. The novelty of this study is that it offers a thorough description of how the controller responds to non-linearities, including temperature changes, which have not received adequate attention in previous studies. This study is expected to expand on these findings by incorporating changing real-world environments into the design and describe a more robust and self-governing PID control approach that can be successfully applied in complicated non-linear systems. The authors' contributions to the field include the incorporation of principles of optimization of PID controllers for more complex and realistic applications, which increases the performance and dependability of fluid control systems in applications: household and industrial.

The objectives of this research are to analyze the impact of temperature-induced fluid viscosity changes on the performance of a PID-controlled plumbing system, demonstrate the effectiveness of the PID controller in maintaining system stability under non-linear conditions, and propose tuning adjustments or strategies to enhance the controller's robustness without increasing computational complexity. This paper is structured to first present the detailed methodology employed for the experimental setup and data collection. Subsequently, the results of the frequency response analysis under various temperature conditions are presented and discussed, highlighting the observed changes in system stability and controller performance. Finally, conclusions are drawn regarding the PID controller's adaptability to nonlinearities, along with recommendations for future research in developing more resilient fluid control systems.

2. METHOD

This work utilizes a closed-loop control system with a PID controller to regulate fluid flow and pressure within a nonlinear plumbing system. The experimental setup employs a multi-loop control demonstrator, which integrates digital pressure sensors and flow meters for real-time data acquisition. The robustness of the control system is evaluated under varying fluid viscosity and temperature conditions.

The overall architecture of the closed-loop control system is depicted in the block diagram in Figure 1. This diagram provides a visual representation of how the PID controller, variable-speed pump, and sensors interact to maintain the desired pressure setpoint. The plumbing setup consists of standard industrial-grade piping with a diameter of 20 mm, equipped with a variable-speed pump for precise adjustment of flow rates. The working fluid is water, whose dynamic viscosity is manipulated by heating the fluid to specific temperatures ranging from 25 °C to 80 °C using an inline heater. This temperature range is chosen to simulate common operational variations encountered in industrial environments. Throughout each test run, temperature sensors, in conjunction with flow meters, continuously record data for flow rates, pressure, and viscosity.

The PID controller is designed to minimize the error between the setpoint (desired pressure) and the measured pressure by adjusting the pump speed. The controller's response is governed by the standard PID control as in (1) [26], where $\mu(t)$ is the control signal to the pump, $e(t)$ is the error between the desired and actual pressure, K_P, K_i, and K_d are the proportional, integral, and derivative gains, respectively. The values for the PID gains were tuned based on initial tests and finalized at K_P = 50, K_i = 15, and K_d = 30. These values were optimized to achieve a stable system response with minimal overshoot and settling time under initial operating conditions.

$$\mu(t) = K_P e(t) + K_i \int_0^1 e(t)dt + K_d \frac{de(t)}{dt}) \quad (1)$$

$$Q = \frac{\pi r^4 (P_1 - P_2)}{8 \eta L} \quad (2)$$

The nonlinear behavior of the system, particularly concerning fluid viscosity changes with temperature, is characterized using the Hagen-Poiseuille equation as in (2) [26], where Q represents the volumetric flow rate, r is the radius of the pipe, $P_1 - P_2$ is the pressure difference between two points, η is the fluid's dynamic viscosity (which varies with temperature), and L is the length of the pipe. This equation is crucial for modeling the system's flow characteristics as it directly reveals the relationship between temperature-induced viscosity changes and the resulting flow rate and pressure variations. To benchmark the adaptability and robustness of the PID controller against changes in viscosity, the following test temperatures were selected: 25 °C, 40 °C, 55 °C, 65 °C, and 80 °C. At each temperature point, flow and pressure data are collected to observe the controller's performance in maintaining system stability. The experimental setup required maintaining a setpoint pressure of 2.0 bar while varying the fluid temperature and corresponding viscosity. For each temperature point, starting from 25 °C up to 80 °C in steps of 15 °C, the system pressure was controlled by the PID controller. Each test run lasted for 30 minutes, with continuous data recording from both pressure and flow rate sensors.

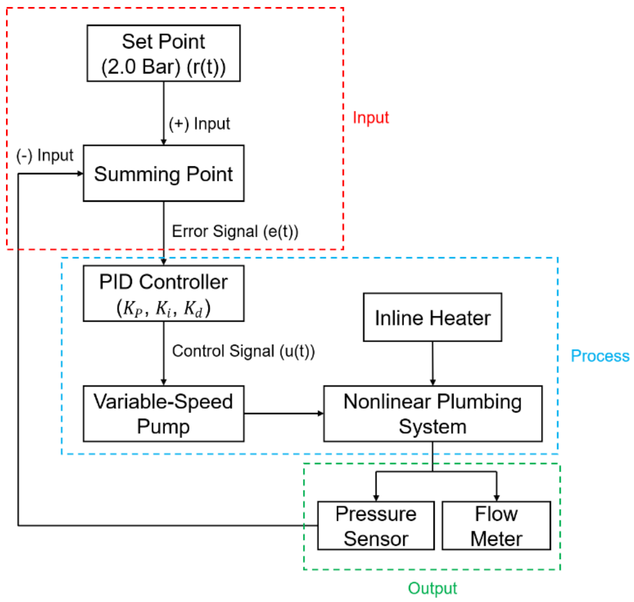


Figure 1. Experimental setup block diagram of the fluid control system

To thoroughly assess system stability and the impact of varying fluid properties, frequency response analysis is conducted using Bode and Nyquist plots. This method is chosen specifically because it provides a comprehensive understanding of how the system responds to different input frequencies, which is crucial for analyzing the effects of changing temperature and viscosity on system dynamics. Variations in temperature and viscosity directly influence the fluid's inertia and resistive forces, altering the system's natural frequencies and damping characteristics. Frequency response analysis allows for the quantification of these changes through gain and phase margins, which are direct indicators of system stability and performance. The frequency response of the system is evaluated using the following Bode plot magnitude in phase (3) and (4) [27]. Here, $M(\omega)$ represents the magnitude response and $\phi(\omega)$ represents the phase shift as functions of angular frequency ω. These plots enable the analysis of the system's performance and stability margins across a range of frequencies, highlighting the PID controller's behavior under different operational conditions. Nyquist plots are generated using the real and imaginary components derived from (5) and (6) [27].

$$M(\omega) = 2log_{10}\left|\frac{Y(j\omega)}{U(j\omega)}\right| \quad (3)$$

$$\phi(\omega) = arg\left|\frac{Y(j\omega)}{U(j\omega)}\right| \quad (4)$$

$$real = M(\omega)x\cos\phi(\omega) \quad (5)$$

$$imaginary = M(\omega)x\sin\phi(\omega) \quad (6)$$

The specific parameters measured in the experimental setup include fluid temperature (in °C), volumetric flow rate (in L/min), and pressure (in bar). The dynamic viscosity of water is implicitly determined by the measured temperature. For each test condition, the following performance metrics were analyzed: overshoot, settling time, and steady-state error. These measurements allow for a direct assessment of the PID controller's ability to maintain the desired pressure setpoint under the tested variations. Regarding the change in phase lag with increasing temperature, as temperature increases, the fluid's viscosity decreases. This typically leads to a faster system response but can also introduce more oscillations and potentially decrease the phase margin, implying a reduction in stability margins. This phenomenon is directly observed and analyzed through the frequency response plots, where a larger phase lag at lower frequencies or a reduction in phase margin indicates a more oscillatory or less stable system.

The development of adaptive control strategies is important for PID-controlled fluid systems operating under fluctuating temperatures because constant PID gains, while optimal at one operating point, may lead to degraded performance or instability when system dynamics change significantly due to viscosity variations. Adaptive strategies can adjust controller parameters in real-time to compensate for these changes, ensuring consistent performance and stability across the entire operational range. This research, by analyzing the system's frequency response under varying conditions, lays the groundwork for understanding the necessity and potential design requirements for such adaptive control mechanisms.

Data analysis involved processing the continuous sensor recordings to extract key performance metrics. No data points were explicitly excluded unless they were clearly identified as sensor malfunctions or transient noise outside the stable measurement period. The collected data for flow, pressure, and temperature were used to calculate system response parameters like overshoot, settling time, and steady-state error for each temperature condition. Furthermore, the collected input-output data were used to generate the frequency response plots, enabling a quantitative assessment of stability margins (gain margin, phase margin) for each viscosity condition. Special attention was given to assessing the controller's performance and robustness in cases of significant viscosity variations, such as high temperature and low viscosity, with a focus on maintaining stability and minimal deviations from the control setpoint.

3. RESULTS AND DISCUSSION

3.1. PID controller performance under baseline conditions

Table 1 presents the PID controller's response under baseline conditions, showcasing the relationship between the error signal (e) and the control signal μ(t) at various time intervals. Initially, the error starts at 2.0 bar, corresponding to a high control signal of 100.0, indicating the pump’s maximal response to reach the desired setpoint. As time progresses, the error gradually decreases. At 5 seconds, the error is reduced to 1.5 bar with a control signal of 80.0, indicating that the controller is adjusting the pump input to compensate for the changing error. By 10 seconds, the error has dropped to 1.0 bar, and the control signal reflects this adjustment with a reduction to 67.5. This trend continues until the error nears zero at 25 seconds, where the control signal settles at 40.0, close to a steady-state level.

Table 1. PID controller performance under baseline conditions

Time (s)	Error (e) (bar)	Control signal $\mu(t)$ (pump input)
0	2.0	100.0
5	1.5	80.0
10	1.0	67.5
15	0.5	54.0
20	0.2	44.5
25	0.0	40.0

The data in Table 1 reveal a smooth reduction in the error signal as the control system stabilizes towards the set point. The gradual decrease in both error and control signal over time aligns with expected PID controller behavior, where the proportional, integral, and derivative components collectively aim to minimize the error without inducing overshoot [13]. The absence of abrupt changes in the control signal $\mu(t)$ suggests well-tuned PID parameters, as the adjustments are neither too aggressive nor too slow [28].

In terms of control dynamics, the PID controller displays a balanced response. The error reduction is steady, indicating a stable rise time [29], [30]. This characteristic is essential in fluid control systems where rapid oscillations or overshoot could potentially disrupt fluid stability and pressure integrity [31]. Here, the control signal's decline corresponds proportionally to the error signal, signifying that the controller is effectively attenuating the error in real-time while avoiding any excessive input that might lead to instability [20].

The data also suggest that the controller avoids excessive or delayed responses that might lead to performance inefficiencies or increased system wear. The lack of overshoot as the error approaches zero supports the conclusion that the PID controller is well-suited for maintaining steady-state conditions without significant oscillations or deviations [32], [33]. This baseline performance provides a benchmark for assessing the PID controller's responsiveness to different operational scenarios, such as changes in fluid viscosity or external disturbances. By establishing the PID controller's ability to stabilize the system under baseline conditions, the results underscore its suitability for fluid control systems where precision and stability are critical [34], [35]. This robust baseline performance is critical, as it serves as the benchmark against which the performance degradation due to varying temperature and viscosity in subsequent experiments can be accurately assessed, thus highlighting the challenges posed by real-world operating conditions.

3.2. Effects of temperature and viscosity on system dynamics

The obtained PID controller performance at various temperatures/viscosities ranging from 25 °C to 80 °C is shown in Table 2. During the tests, set point pressure was kept at 2.0 bar. It is obvious that when the temperature increases, the viscosity of the fluid decreases, which causes remarkable changes in system behavior. Indeed, such changes are going to affect the performance indices such as overshoot, settling time, and steady-state error. At 25 °C, the system operates relatively stably, with a measured pressure of 2.05 bar, an overshoot of 3.1%, and a flow rate of 10.2 L/min. The steady-state error is minimal at 2.5%, indicating good control under baseline conditions. As the temperature rises to 40 °C, the viscosity drops to 0.8 mPa·s, causing the measured pressure to increase slightly to 2.11 bar. The overshoot increases to 5.2%, and the settling time extends to 26 seconds, reflecting the system's growing difficulty in maintaining rapid stabilization.

Table 2. PID controller performance under varying temperature and viscosity conditions

Temperature (°C)	Viscosity (mPa s)	Set point pressure (bar)	Measured pressure (bar)	Flow rate (L/min)	Overshoot (%)	Settling time (s)	Steady-state error (%)
25	0.9	2.0	2.05	10.2	3.1	24	2.5
40	0.8	2.0	2.11	11.0	5.2	26	5.1
55	0.7	2.0	2.17	11.5	7.4	28	7.2
65	0.6	2.0	2.22	12.1	10.2	32	10.4
80	0.5	2.0	2.31	13.0	15.7	38	14.7

As the temperature reaches 55 °C, the viscosity further decreases to 0.7 mPa·s, resulting in a measured pressure of 2.17 bar and a flow rate of 11.5 L/min. The overshoot escalates to 7.4%, and the settling time extends to 28 seconds, showing a clear trend of reduced control precision. At 65 °C, the measured pressure increases to 2.22 bar, and the flow rate climbs to 12.1 L/min. The overshoot and settling time increase significantly to 10.2% and 32 seconds, respectively, indicating that the control system is struggling to maintain stability [36]. At the highest tested temperature of 80 °C, the viscosity drops to

0.5 mPa·s, causing the measured pressure to rise to 2.31 bar and the flow rate to reach 13.0 L/min. The overshoot peaks at 15.7%, and the settling time extends to 38 seconds. Also, the settling time increases considerably, up to 14.7%, which means that the PID controller is not able to cope with fast changes of the fluid properties effectively [37]. This inability to effectively cope with rapid changes in fluid properties, particularly the significant increase in steady-state error, directly translates to a reduced precision in maintaining the desired setpoint. In practical applications, this lack of precision can lead to substantial energy waste due to sustained deviations from optimal operating points, compromised product quality in processes requiring tight fluid control, and increased wear on system components from prolonged periods of instability.

Since the viscosity of the fluid decreases with the increase in temperature, a lesser damping effect on the system and more responsiveness to control inputs would be provided. On the other hand, it also becomes more susceptible to overshoot, therefore longer settling times-as depicted by the increase in their values shown in Table 2. The rise in overshoot and settling time with temperature suggests that the PID controller's predictive capabilities are being challenged by the non-linear changes in fluid properties [38]. The observed rise in overshoot and settling time not only signifies a diminished ability of the PID controller to predict and counteract system disturbances but also indicates a compromised operational efficiency. A longer settling time means the system takes more time to stabilize after a disturbance, reducing throughput in continuous processes, while increased overshoot can lead to undesirable temporary excursions from the setpoint, potentially affecting safety or material integrity. This leads to larger deviations from the set point before the system stabilizes, clearly indicating a necessity for more sophisticated control strategies that can adapt to such real-time variations. For instance, without such adaptive measures, industrial processes relying on precise fluid dynamics would face inconsistent output, higher operational costs due to energy inefficiency, and increased risks of system failures due to prolonged instability [39], [40].

Moreover, the increase in steady-state error at higher temperatures indicates that the PID controller struggles to maintain accurate control as the fluid becomes less viscous [41]. This is particularly problematic in applications where precise pressure and flow control are critical, such as in industrial processes where maintaining consistent fluid dynamics is essential for operational efficiency and safety [42]. Therefore, the increasing steady-state error and degraded transient response underscore the limitations of a fixed-parameter PID controller in dynamic environments, necessitating advanced solutions to ensure operational consistency and reliability in critical industrial fluid systems. These findings underscore the limitations of conventional PID controllers in managing non-linear system dynamics caused by environmental changes.

3.3. Non-linear behavior analysis

Results of the system's nonlinear behavior concerning temperature and viscosity changes are given in Table 3. It can be observed that the system, at 25 °C, oscillates hardly with a frequency of 0.2 Hz and peak-to-peak amplitude of 0.04 bar. The stability measure, in this case, possesses a reasonably high value of 0.92 and suggests this operating point to be stable with minimal perturbations [13]. With increasing temperature, viscosity decreases and the oscillation frequency rises gradually, as does the peak-to-peak amplitude. For example, at 40 °C, the frequency climbs to 0.4 Hz, with a peak-to-peak amplitude of 0.07 bar and stability of 0.85. This trend continues, and the oscillation frequency and amplitude of the system notably increase to a maximum frequency and amplitude of 1.1 Hz and 0.20 bar, respectively, at 80 °C, while the stability indicator significantly drops to 0.50. This significant drop in the stability indicator to 0.50 at 80 °C is a critical finding, implying that the system approaches a point where persistent oscillations can lead to component fatigue, energy losses, and even catastrophic failures in sensitive industrial applications. The increased oscillations represent wasted energy as the controller continuously overcorrects, and they can directly impact the quality of the processed fluid or product within the system.

Table 3. Experimental data for non-linear system behavior under extreme temperature and viscosity variations

Temperature (°C)	Viscosity (mPa s)	Oscillation frequency (Hz)	Peak-to-peak amplitude (bar)	Stability indicator (0-1)
25	0.9	0.2	0.04	0.92
40	0.8	0.4	0.07	0.85
55	0.7	0.6	0.11	0.75
65	0.6	0.8	0.15	0.65
80	0.5	1.1	0.20	0.50

As temperature rises and viscosity decreases, the control system becomes increasingly susceptible to oscillations [12]. This effect is illustrated by both the rising oscillation frequency and peak-to-peak amplitude. These results reflect the challenges of maintaining steady control as fluid properties fluctuate under extreme conditions. The decreasing stability indicator corroborates these findings, as it diminishes steadily from 0.92 at 25 °C to 0.50 at 80 °C, highlighting the loss of system stability under high temperature and low viscosity scenarios. This consistent decline in the stability indicator from 0.92 to 0.50 directly illustrates the PID controller's struggle to maintain effective damping and error reduction as fluid properties become more variable. The 'so what' here is that without an adaptive mechanism, the system risks prolonged periods of instability, rendering the control ineffective for precise applications.

This non-linear behavior suggests that the PID controller, while effective under baseline conditions, may struggle to maintain stability as the fluid dynamics become more variable [43]. The increased oscillation amplitude at higher temperatures points to the controller’s difficulty in dampening fluctuations under non-linear conditions [44]. This pattern is critical in applications where significant temperature variations are expected, as it conclusively signals the necessity for adaptive control strategies or additional compensatory mechanisms to maintain stability and performance, rather than merely suggesting a potential need [45].

In sum, the results underscore the impact of non-linear behavior on PID control performance in fluid systems. The PID controller's capacity to respond to non-linear dynamics is limited by its fixed parameters, which may not be sufficient to counteract extreme shifts in fluid characteristics. This analysis suggests that for systems operating under broad temperature ranges, additional control techniques—such as gain scheduling or adaptive control—may be necessary to sustain performance and ensure stability across varying operating conditions. Therefore, the observed non-linear behavior definitively limits the applicability of conventional, fixed-parameter PID controllers in scenarios with wide operational ranges. The findings from this analysis strongly advocate for the integration of advanced control techniques, such as gain scheduling or adaptive control, to ensure sustained performance and stability across varying operating conditions in fluid systems.

3.4. Frequency response and stability margins

Figure 2(a) shows the Bode diagram, which illustrates the frequency response of the system under varying temperature conditions. The gain and phase values are presented for different temperatures, ranging from 25 °C to 80 °C. As temperature increases, both gain and phase shift show a consistent trend, indicating the system's behavior under different operational environments. To describe the relationship between gain and phase, a linear regression model was developed, resulting in (7).

$$\phi(\omega) = 3.14\ x\ M(db) - 102.214 \tag{7}$$

The (7) has an R^2 value of 0.9985, indicating an excellent fit to the experimental data. This suggests that the relationship between gain and phase is nearly perfectly linear within the tested temperature range. The equation allows for accurate prediction of phase values based on gain, making it a useful tool for understanding the system's stability margins and behavior under different conditions.

From the experimental results, the following trend is observed in the Bode diagram: with an increase in temperature, the gain of the system decreases with phase lag. These frequency response characteristics may vary due to the changes in viscosity and density within the properties of the fluid. With the rise in temperature of the working fluid, its viscosity goes down, which causes less damping and thus a shift in dynamic behavior accordingly. Directly, this can influence the stability of the system because, as shown, the phase lag has increased while the gain is reduced continuously. The linear relationship between gain and phase would reflect that the system is predictable under conditions of varied temperature, a fact necessary for designing robust control strategies [22]. The high R^2 value indicates that the model will represent the data quite well and, therefore, can be reliable for predicting the system's response for temperatures outside of this tested range.

The observed trend in the Bode diagram, where the gain of the system decreases with increasing phase lag as temperature rises, holds significant implications for system stability. A decreasing gain margin (implicitly suggested by gain reduction) and an increasing phase lag directly indicate a reduced margin of stability; that is, the system becomes more oscillatory and closer to instability. This is critical because in real-world fluid control, a system with lower stability margins is more susceptible to disturbances and less capable of recovering quickly from upsets, potentially leading to persistent oscillations or complete loss of control. The linearity of the gain-phase relationship further underscores that these changes are predictable and can thus be characterized, but they still represent a clear challenge to a fixed-gain PID controller.

In the work [46], a PIDDα controller was developed to improve performance in industrial processes, including pressure and flow systems. Their research primarily focused on optimizing time-domain metrics such as overshoot and settling time, demonstrating that their proposed controller outperformed conventional PID techniques by achieving significantly lower overshoot (4.83% for a pressure plant) and faster settling times (8.95 s). While their work highlights the limitations of standard PID controllers in nonlinear and unpredictable environments, our study complements this by analyzing the robustness of a classic PID controller under a specific, real-world nonlinear disturbance—namely, changes in fluid viscosity due to temperature. Our use of frequency response analysis provides a different lens, quantifying system stability through gain and phase margins, which directly relate to the system's resilience against variations in dynamics.

In previous analysis, it was observed that the PID controller's performance was significantly affected by temperature and viscosity variations, leading to changes in overshoot, settling time, and steady-state error. These findings are consistent with the frequency response analysis, where increased temperature results in a more significant phase lag and reduced gain, indicating a less responsive system [47]. The frequency response analysis complements the earlier transient and steady-state performance evaluations by providing a comprehensive understanding of how the system behaves across a range of frequencies. This information is crucial for assessing the controller's robustness, particularly in maintaining stability under extreme operating conditions.

The work [48] also investigated PID and FOPID controllers, but within the context of a highly complex nuclear-renewable hybrid energy system. Their approach involved using a metaheuristic optimization algorithm (ABC) to optimally tune the controller parameters to ensure system stability. This is in contrast to our study, which uses a fixed set of pre-tuned PID gains to specifically investigate how a non-optimized controller's performance and stability margins degrade as the system's physical properties (viscosity) change. Their work demonstrates a solution (optimal tuning) for ensuring stability in complex, multi-input systems, while our research provides foundational data on the problem that such solutions must address—the inherent instability that arises when a single set of gains is used in a system with significant dynamic variations.

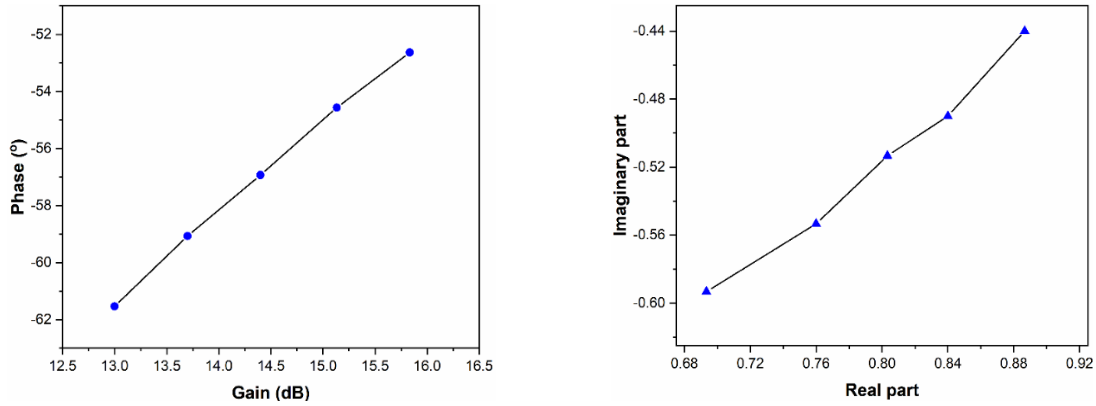
The decision to employ frequency response analysis, particularly Bode and Nyquist plots, was critical because it precisely quantifies the system's dynamic characteristics under varying conditions, providing insights that time-domain analysis alone cannot. The phase lag, for instance, represents the time delay in the system's response to an input signal; as temperature increases and viscosity decreases, this phase lag tends to increase. This implies that the controller's corrective action arrives later relative to the system's dynamic state, exacerbating the overshoot and settling time observed in the time-domain results. The Nyquist plot, by mapping the entire frequency response, directly visualizes the system's proximity to instability by its trajectory relative to the critical point (−1,0). The observed leftward and downward shift in the Nyquist plot with increasing temperature unequivocally confirms a deterioration in stability margins, demonstrating the system's increased vulnerability to oscillations and reduced damping at higher temperatures and lower viscosities. This comprehensive frequency-domain perspective directly informs why the PID controller struggles and what specific dynamic changes occur due to temperature-induced viscosity variations.

Figure 2(b) presents the Nyquist plot that illustrates the real and imaginary components of the system's frequency response under various operational conditions (temperature). This analysis is crucial for evaluating the stability margins of the PID-controlled fluid system, particularly under non-linear behavior conditions such as varying temperature and viscosity [49]. The Nyquist plot provides a comprehensive view of the closed-loop system's stability by mapping the real and imaginary components of the frequency response [50]. The system's trajectory in the Nyquist diagram indicates its stability characteristics [51], with the system remaining stable as long as the plot does not encircle the critical point (−1,0). The data points in the table demonstrate how the real and imaginary components of the response change with temperature variations.

As observed from the Nyquist plot, the data points progressively shift leftward and downward as the temperature increases from 25 °C to 80 °C. This shift indicates a reduction in gain margin and an increase in phase lag, as evident from the decreasing real component and increasing negative value of the imaginary component [50]. This trend aligns with the earlier Bode plot analysis, where an increase in temperature led to a decrease in gain and phase, suggesting that higher temperatures cause the system to become less responsive and more prone to instability.

The reduction in the Nyquist plot's real component (from 0.89 at 25 °C to 0.69 at 80 °C) and the more negative imaginary component indicate that the system's damping decreases with rising temperatures. This behavior corresponds with the increase in overshoot and settling time observed in the time-domain analysis of PID controller performance under varying temperature and viscosity conditions (Table 2). The increased overshoot and longer settling times signify that the system struggles to maintain stability and swiftly return to its set point under higher temperature conditions [27]. The frequency response data from the Bode and Nyquist plots complement each other, providing a comprehensive picture of the system's dynamic behavior.

Furthermore, the study in [52] proposed a decentralized optimal PID controller for higher-order industrial systems, which, like our study, relies on frequency domain specifications such as gain and phase margins for robust stability analysis. A key distinction, however, is that their work addresses the complexities of multi-input multi-output (MIMO) systems, using advanced techniques like 'disk margin-based analysis' to manage loop interactions. In contrast, our study focuses on a simpler single-input single-output (SISO) system, where we use traditional Bode and Nyquist plots to characterize the stability margins. Our research provides a fundamental analysis of how these conventional stability margins, which are often used in SISO systems, are directly impacted by changing physical parameters, thereby laying the groundwork for more advanced robust stability analyses like those used in their work.



(a) (b)

Figure 2. Frequency response analysis of the PID-controlled fluid system under varying temperature and viscosity conditions: (a) Bode plot illustrating the gain in dB and phase in ° and (b) Nyquist plot visualizing the real and imaginary components of the system's frequency response

The decrease in gain and phase margins observed in the Bode plot is mirrored in the Nyquist plot as a reduction in the real component and increased deviation in the imaginary component. This consistency validates the experimental results and highlights the challenges posed by non-linearities in maintaining system stability, particularly under extreme operating conditions. This consistent evidence from both time-domain and frequency-domain analyses unequivocally demonstrates that while the PID controller is effective under stable baseline conditions, its fixed parameters render it increasingly ineffective in mitigating the dynamic challenges introduced by temperature-induced viscosity variations, thereby confirming the inherent limitations of conventional PID control in such highly nonlinear fluid systems.

3.5. Implications for industrial application

The findings of this study hold significant implications for industrial fluid systems, particularly those requiring precise control of pressure and flow rates under varying environmental conditions. In industries such as chemical processing, water treatment, and HVAC systems, maintaining stability in fluid dynamics is crucial for operational efficiency [19], [53] and safety [54]. In industries such as chemical processing, water treatment, and HVAC systems, maintaining stability and precision in fluid dynamics is paramount for operational efficiency and safety. While the PID controller's performance, as evaluated in this research, demonstrates its effectiveness in managing fluid systems under nominal conditions, the results also starkly highlight its significant limitations when the system operates under extreme conditions—such as higher temperatures—where non-linearities considerably reduce the controller's effectiveness and lead to degraded performance [36].

We will emphasize two important results of this work: first, how the temperature and viscosity of the fluid affect the dynamic response of the system, and second, with the increased temperature, the viscosity of the fluid is reduced, which results in greater flow rates and more instability in the regulation of pressure within the system [55], [56]. This effect was clearly observed through the increased overshoot, longer settling times, and higher steady-state errors at elevated temperatures.

The observed increase in overshoot, longer settling times, higher steady-state errors, and increased oscillations at elevated temperatures are not merely theoretical degradations; they translate directly into tangible industrial challenges. For instance, in chemical reactions, temperature-induced flow rate variations can lead to off-spec products or unsafe exothermic reactions. In water treatment, inconsistent pressure can cause pump damage or inefficient filtration. These dynamic instabilities result in increased energy consumption due to constant overcorrection, higher maintenance costs from accelerated component wear, reduced throughput in production lines, and critically, potential safety hazards due to unpredictable system behavior. This strongly underscores that temperature control and compensation are not merely supplementary but must be meticulously managed in systems with significant thermal variations to prevent fluctuations that could impair product quality or lead to critical system failures.

The frequency response analysis, including both Bode and Nyquist plots, further underscores the importance of understanding the system's stability margins under varying operational conditions. As the gain and phase margins decrease with rising temperature, the system becomes more susceptible to oscillations and reduced damping. In industrial applications, this reduction in stability could lead to inefficient operation, excessive wear on components, or even safety hazards. Thus, the compelling evidence from this study suggests that while conventional PID control remains a valuable foundational tool, its inherent limitations in highly nonlinear environments necessitate the adoption of adaptive or more advanced control strategies. Specifically, model predictive control (MPC) or gain-scheduling PID approaches emerge as crucial solutions to maintain robust performance under non-linear and extreme conditions [57], [58]. These strategies, by dynamically adjusting controller parameters or predicting future system states, can effectively counteract the adverse effects of temperature-induced viscosity changes, thereby ensuring sustained stability and efficiency.

Furthermore, the insights gained regarding the PID controller's limitations under specific environmental conditions provide a critical guide for the design of future fluid systems. By explicitly accounting for the effects of temperature and viscosity variations in the early stages of system design, engineers can proactively optimize their systems for long-term stability and performance, incorporating features such as integrated temperature compensation techniques, real-time viscosity sensors for feedback, and dynamically tunable PID parameters to ensure consistent control across wide operational ranges. This proactive approach, informed by the findings, will lead to more resilient, efficient, and safer fluid control systems in diverse industrial applications.

4. CONCLUSION

This research aimed to explore the effects of temperature and viscosity variations on the performance of a PID-controlled fluid system, focusing on system dynamics, stability, and efficiency. The study demonstrated that increasing temperature decreases fluid viscosity, leading to higher flow rates and introducing non-linear behavior, resulting in greater overshoot (from 3.1% to 15.7%), longer settling times (from 24 s to 38 s), and reduced stability margins. The Bode and Nyquist frequency analyses further highlighted these challenges, indicating that while the PID controller performs well under normal conditions, it struggles with stability in extreme scenarios. These findings are crucial for industries like chemical processing, where precise fluid control is vital, and suggest that future research should focus on the development of adaptive control strategies to dynamically adjust controller parameters, thereby ensuring robust performance and maintaining stability margins across the full range of operational conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Herri Trisna Frianto	✓			✓	✓	✓		✓	✓					
Syahrul Humaidi	✓						✓			✓		✓		✓
Kerista Tarigan	✓	✓		✓			✓			✓				
Dadan Ramdan					✓			✓		✓		✓		
Doli Bonardo					✓				✓		✓		✓	

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SH], upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Herri Trisna Frianto has been involved in academia and industry with a strong background in electrical engineering and control systems. He earned his bachelor's degree and later completed his master's studies at Institut Teknologi Medan in 1998 and Institut Sains dan Teknologi Nasional in 2010. Currently, he teaches a variety of subjects, including electrical circuit practice, PLC, PLC practice, control systems, and control systems practice. His dedication to community service is evident through initiatives like the PLC device usage training SCADA at SMK Nusantara Kreatif Mandiri in Binjai, Sumatra Utara. His areas of research and teaching continue to impact both his students and the local community. He can be contacted at email: htfriantosjafri@gmail.com.

Syahrul Humaidi is an associate professor at the Department of Physics, Faculty of Mathematics and Natural Science, Universitas Sumatera Utara, Medan, Indonesia, where he has been a faculty member since 1995. Humaidi earned his bachelor's degree in physics from Universitas Sumatera Utara in 1985, followed by an M.Sc. in physics from Universiti Teknologi Malaysia, Johor, Malaysia, in 2000. He completed his Ph.D. in material physics at Universitas Sumatera Utara, Medan, Indonesia, in 2017. His research interests include advanced functional materials, materials for electronics, and biomaterials, and he has authored or co-authored over 60 research publications. He can be contacted at email: syahrul1@usu.ac.id.

Kerista Tarigan obtained his Bachelor of Science in physics from Universitas Sumatera Utara, Medan, Indonesia, in 1985, followed by a Master of Science in Engineering in optoelectronics from the University of Indonesia, Jakarta, Indonesia, and earned his Ph.D. in physics from Universitas Sumatera Utara, Medan, Indonesia. He also served as the secretary of the master's program in the department. Currently, he is a lecturer at the Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara, Medan, Indonesia. His research interests include material electronics, composite physics, control systems, semiconductor physics, and physicochemistry. He can be contacted at email: kerista@usu.ac.id.

Dadan Ramdan is a professor at the Department of Mechanical Engineering, Faculty of Engineering, Universitas Medan Area, Medan, Indonesia. He obtained his Bachelor of Science in instrumentation physics from Padjajaran University, Bandung, Indonesia. Additionally, he earned his Master of Science in instrumentation physics from Bandung Institute of Technology, Bandung, Indonesia, and his Master of Engineering in production system engineering from Toyohashi University of Technology, Aichi, Japan. He also holds a Ph.D. in mechanical engineering from Universiti Sains Malaysia, Penang, Malaysia. He currently holds the position of rector at Universitas Medan Area, Indonesia. His research interests encompass control system engineering, energy conversion, manufacturing engineering, and instrumentation engineering. He can be contacted at email: dadan@uma.ac.id.

Doli Bonardo completed his undergraduate education in physics at Universitas Negeri Medan, graduating in 2017. The title of his thesis was "Synthesis and Characterization of Silica Nanoparticles from Sugarcane Bagasse Ash as Aluminum Filler". Subsequently, he pursued a master's degree in physics at Universitas Sumatera Utara, where he graduated in 2021. His master's thesis was titled "Synthesis and Characterization of NO2 Gas Sensor Sensitive Layer Based on WO3 Using Hydrothermal Method". He teaches several subjects, including physics I, electrical circuits 1, digital electronics, discrete mathematics, linear algebra, and fundamentals of digital systems. He can be contacted at email: dolibonardo@umrah.ac.id.