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PID-Controlled Pyrolysis of Medical Mask Waste for Enhanced Alternative Fuel Production

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ABSTRACT

The escalating volume of plastic-based medical mask waste, exacerbated by the COVID-19 pandemic, presents an urgent environmental challenge that can be addressed through sustainable valorization. This study proposes a novel, integrated approach by evaluating the effectiveness of a Proportional-Integral-Derivative (PID) temperature control system to minimize thermal fluctuations critical for consistent product selectivity of the pyrolysis process. A rigorous comparative evaluation of the Cohen-Coon (CC) and Internal Model Control (IMC) tuning methods demonstrated IMC's superiority, achieving a significantly shorter settling time of 114 minutes and a low overshoot of 0.45, ensuring stable isothermal operation. Pyrolysis process conducted under this optimized control condition (at 250°C for 5 hours) resulted in high liquid fuel yields and improved physical characteristics (density 785.8 kg/m^3, viscosity 1.546 cSt). Gas Chromatography-Flame Ionization Detector (GC-FID) confirmed that the liquid fuel exhibits hydrocarbon fractions highly similar to commercial kerosene and diesel. These findings underscore that the precision of the IMC-PID method is the key technical enabler for enhancing both process stability and the subsequent quality and yield of valuable liquid fuel derived from medical mask waste.

Keywords: medical masks, PID controller, pyrolysis, tuning, waste-to-energy.

1. INTRODUCTION

The outbreak of Coronavirus Disease 2019 (COVID-19) has significantly increased the global consumption of medical masks, primarily to prevent viral transmission through respiratory droplets. According to the World Health Organization (WHO), billions of single-use face masks are discarded daily, creating a substantial source of plastic-based medical waste [1]. Medical masks are typically composed of polypropylene (PP), polyethylene, polyurethane, and other synthetic polymers, which are non-biodegradable and persist in the environment for decades [2,3]. Their improper disposal contributes not only to microplastic pollution but also to potential secondary transmission of infectious agents. Consequently, the accumulation of mask waste has become an urgent environmental and public health issue [4–7].

Conventional medical waste treatment, such as incineration and landfilling, is heavily criticized for its environmental drawbacks. Incineration at high temperatures (800–1000°C) can reduce waste volume effectively, but it generates hazardous emissions including dioxins, furans, and particulate matter. Landfilling, on the other hand, occupies large areas and risks long-term soil and groundwater contamination due to the persistence of polymeric materials. Hence, alternative approaches that are both environmentally friendly and technically feasible are urgently required [8–10].

Pyrolysis has emerged as a promising thermochemical conversion process for addressing plastic and medical waste challenges. It involves the decomposition of polymers at elevated temperatures in the absence or near absence of oxygen,

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producing three main products: solid char, non-condensable gases, and liquid oil. The liquid fraction, often referred to as pyrolysis oil, contains hydrocarbons suitable for use as alternative fuels. Several studies have demonstrated that pyrolysis of plastics such as polyethylene, PP, and polystyrene yields liquid fuels with calorific values comparable to conventional fossil fuels. Importantly, pyrolysis provides a dual benefit: reducing plastic waste volume while generating valuable energy resources [11,12].

Recent investigations confirm the feasibility of converting PP-based medical masks into valuable liquid fuel. For instance, Park, et al. (2021) conducted pyrolysis of KF94 medical masks at temperatures between 500–900°C and identified hydrocarbon fractions resembling gasoline, kerosene, and diesel [13]. Similarly, the other studies reported successful pyrolysis of polyethylene plastics at controlled temperatures, highlighting the role of temperature in influencing product distribution and fuel properties. Collectively, these studies highlight the potential of pyrolysis as a sustainable pathway for managing medical mask waste [14–16]. These studies collectively underscore the critical, yet often inadequately addressed, role of precise temperature control in influencing product distribution and fuel properties.

Despite these advances, a persistent challenge is the precise control of temperature. Thermal fluctuations promote non-selective secondary cracking, resulting in a broader product spectrum and inconsistent fuel quality, particularly for the desired C10−C20 fractions [17,18]. In industrial practice, Proportional-Integral-Derivative (PID) controllers are widely used to regulate process variables due to their robustness and simplicity. However, The effectiveness of PID controllers depends heavily on the accuracy of tuning parameters—Controller Gain (Kc), Integral Time (τ_I), and Derivative Time (τ_D), which determine system responsiveness, stability, and error minimization [19].

Several tuning methods have been developed to optimize PID controller performance. The Cohen-Coon (CC) method provides rapid response characteristics but may result in higher overshoot [19,20]. Conversely, the Internal Model Control (IMC) approach integrates process models to achieve more stable and accurate control with minimal error [21,22]. While tuning strategies like Cohen-Coon (CC) and Internal Model Control (IMC) have been applied generally, a fundamental and quantitative investigation linking superior PID controller performance parameters (e.g., minimal overshoot and short settling time) directly to the resulting physico-chemical properties of pyrolysis oil from medical mask waste remains conspicuously absent in the literature.

Filling this critical knowledge gap, this study systematically evaluates the influence of CC and IMC tuning methodologies on PID controller performance during medical mask pyrolysis, aiming to establish the optimal control strategy. Furthermore, we quantify the resulting impact of this optimized thermal stability on the yield of liquid fuel, key physical properties (density, viscosity), and hydrocarbon composition. By pioneering the integration of advanced process control with waste-to-energy conversion, this research provides the first systematic evidence that the IMC tuning method is the key technical enabler for maximizing the yield and quality of liquid fuel comparable to commercial kerosene and diesel.

2. RESEARCH METHODS

2.1. Materials

The raw material consisted of commercially available, non-sterile Type IIR three-ply medical masks, adhering to EN 14683 standard. The primary polymer component of the mask is Polypropylene (PP) (≈90% w/w), with minor presence of polyethylene in the outer/inner layer. A total of 250 g of shredded masks was used as the feedstock for each pyrolysis batch. The masks were shredded into approximately 1 × 1 cm pieces

to facilitate uniform heat transfer. This particle size was chosen to maximize the external surface area-to-volume ratio for effective heat transfer. Before processing, the masks were oven-dried at 105°C for 2 hours to remove moisture.

Commercial fuels, namely gasoline, kerosene, and diesel, were purchased from local fuel stations and used as reference standards for comparative analysis of density, viscosity, qualitative observation, and GC-FID analysis. Nitrogen gas (99.9% purity) was supplied from high-pressure cylinders and employed to purge the reactor before pyrolysis in order to minimize oxidation.

2.2. Pyrolysis Reactor System

Pyrolysis experiments were conducted in a laboratory-scale batch reactor system with a total capacity of 3 kg. The reactor was fabricated from stainless steel (grade 304) with a diameter of 2 cm to withstand temperatures up to 600°C [23]. Heating was provided by an electric furnace with a rated power of 1.5 kW, which was wrapped around the reactor.

The condenser unit consisted of a stainless-steel tube-in-shell heat exchanger cooled by circulating tap water at 20–25 °C. Condensed liquid products were collected in a glass receiving flask connected downstream of the condenser. A vacuum pump was installed to facilitate gas flow and enhance condensation efficiency.

2.3. PID Control System

The Controlled Variable (CV) was the internal reactor temperature, measured by a type-K thermocouple (±2°C accuracy) placed at the center of the feedstock bed. The Manipulated Variable (MV) was the power supply to the furnace, regulated via a Solid-State Relay (SSR). Control logic was implemented using an Arduino Nano and a MAX6675 amplifier for signal conditioning. A 4×4 keypad was installed to allow manual input of setpoints.

2.4. PID Tuning Procedure

The dynamic behavior of the reactor was first characterized using the Ziegler-Nichols Open-Loop Step Response Method (also known as the Process Reaction Curve method). The resulting response was approximated by a First-Order Plus Dead Time (FOPDT) model, allowing extraction of the process gain (Kp), time constant (τ), and dead time (τd) were extracted to obtain the transfer function model.

Two tuning methods were applied to determine the controller parameters: 1.) Cohen-Coon (CC) method – providing aggressive control action with faster rise time but potentially higher overshoot. 2.) Internal Model Control (IMC) method – offering smoother control with reduced overshoot and better disturbance rejection. The calculated parameters (Kc, τ_I, and τ_D) were coded into the Arduino PID algorithm. Controller performance was quantitatively evaluated based on overshoot, rise time, settling time, and steady-state error (offset).

2.5. Pyrolysis Procedure

Each pyrolysis experiment was carried out with 250 g of medical mask feedstock under two different temperature setpoints: 220°C and 250°C. Prior to heating, the reactor was purged with nitrogen gas at 1 L/min for 10 minutes to remove residual oxygen. The reactor was heated at a controlled rate of 10°C/min until the setpoint was reached, and the isothermal condition was maintained for a holding time of 5 hours. During operation, the non-condensable gases were vented through the condenser and collected in a gas sampling trap for safety. The condensed liquid was collected at the outlet flask, while solid char residues were retrieved from the reactor after cooling. The product yield (wt%) for char, liquid, and gas was calculated on a mass basis relative to the initial oven-dried feedstock mass.

2.6. Product Separation and Characterization

The condensed liquid product typically contained immiscible phases consisting of a hydrocarbon-rich fraction (pyrolysis oil), a clear aqueous-like phase, and a cloudy intermediate phase. The mixture was separated using a 500 mL separatory funnel, allowing gravity-driven phase separation for 1 hour. The pyrolysis oil fraction was subjected to the following analyses:

- Density: measured using a 25 mL pycnometer at 15°C in accordance with ASTM D4052.
- Kinematic viscosity : measured at 40°C using an Ostwald viscometer following ASTM D445.
- Qualitative observation : 25 untrained panelists assessed the color and odor of the fuel relative to kerosene and diesel using a 5-point hedonic scale.
- Hydrocarbon composition : Analysis was performed using a system equipped with a non-polar capillary column (30 m × 0.25 mm × 0.25 μm film thickness). The carrier gas was Helium (1 mL/min). The oven temperature program ranged from 50°C (hold for 5 min) to 300°C at a rate of 10°C/min. Prior to injection, the pyrolysis oil sample was diluted 1:10 (v/v) with n-Hexane (HPLC Grade) to ensure optimal sample volatility and prevent column overload. Commercial reference samples (kerosene and diesel) were similarly diluted. Reference samples of kerosene and diesel were injected for comparative retention time analysis.

3. RESULTS AND DISCUSSION

3.1. Process Dynamic Identification

Precise temperature control is a critical parameter for ensuring consistent product selectivity during batch pyrolysis. The chosen low-temperature regime (220°C and 250°C) was strategic, favoring the thermal decomposition of low-molecular-weight fractions and minimizing non-condensable gas formation typically observed above 400°C. This low-temperature operation benefits significantly from superior PID control stability, minimizing the risk of thermal runaway associated with exothermic decomposition.

Adjustments must be performed to provide a satisfactory system response in temperature control during the medical mask pyrolysis process. The tuning parameters (Kc, τ_I, and τ_D) were calculated after finding the transfer function.

3.1.1. Process Transfer Function Identification

The reactor dynamics were characterized using the Ziegler-Nichols Open-Loop Step Response Method. A step change in power output from 55.556% to 100% resulted in a steady-state temperature change from 58.15% to 81.11%. The system was successfully approximated as a First-Order Plus Dead Time (FOPDT) model (Figure 1), yielding the following key parameters: Process Gain (Kp): 0.52, Time Constant (τ): 12 minutes, and Dead Time (τd): 8 minutes.

Retain the strong argument: The observed τd of 8 minutes is significant, primarily attributed to the high thermal inertia of the stainless steel reactor wall and the inherent conduction delay through the 250 g of shredded mask feedstock. This large dead time imposes a severe constraint on conventional controller tuning. The τd value is acquired for 8 minutes due to the involvement of detector instruments (thermocouple and transmitter) in calculating the transfer function, each of which requires a specific time period (τd) to produce an output signal. The position of the transmitter sensor in relation to the recording equipment (the Arduino nano controller) is the primary factor influencing τd values. The dead time or delay time is governed by the distance of the sensor from the controller; the more distant the position, the greater the delay time [24].

Equation 1 shows a general equation that can be used to model the temperature controller's transfer function as First Order Plus Dead Time (FODT).

$$G(s) = \frac{Kp\, e^{-\tau ds}}{\tau s+1} \quad (1)$$

$$Kp=\Delta PV/\Delta PO \quad (2)$$

$$\Delta PO = PO2-PO1 \quad (3)$$

$$\Delta PV\ PV2-PV1 \quad (4)$$

PV = Process Variable, PO = Power Output, in % and % respectively, Kp is unitless.

Equation 5 represents the transfer function equation for the PID controller in the medical mask pyrolysis process, derived from the generic transfer function equation (1).

$$G(s) = \frac{0{,}52\, e^{-8s}}{12s+1} \quad (5)$$

3.1.2. Controller Tuning Comparison and Performance

Following the calculation of the transfer function value, control settings (tuning) can be determined. Ziegler-Nichols (ZN), Cohen-Coon (CC), and Internal Model Control (IMC) are common tuning approaches. The CC and IMC approaches were employed in this study for tuning. The CC and IMC tuning methods were selected because they provide a robust and practical solution for processes characterized by significant dead time and thermal inertia, such as batch pyrolysis. Unlike complex adaptive controllers, which require sophisticated computing, the model-based IMC offers an optimal balance between control performance and implementation simplicity, making it highly suitable for industrial upscaling in this specific low-temperature regime. The CC method was chosen due to tuning using the CC method has the advantage of a response that moves faster to reach the set point than the ZN method. This is because the CC method is a development of the ZN method, where CC is a more complex version than the ZN method and provides faster rise times [25].

The IMC method was chosen because it can reduce errors by comparing the process output to the expected output using an inverse model, making it suitable for optimizing PID controllers [26]. Aside from that, these two tuning methods are simpler to use and more efficient, as they allow calculating two methods at the same time, CC and IMC, using a single transfer function. The IMC approach is influenced by the τc value, which distinguishes it from the other method.

Choosing the right τc value is crucial for regulating the IMC method. Increasing the τc value results in a conservative controller, as it decreases the Kc value [27].

The τc value utilized in this study is τc = 0.5 (τ + τd), as the transfer function calculation yields a somewhat long τd value. The CC approach yielded Kc = 4.35, τ_I = 15.71 minutes, and τ_D = 2.59 minutes. The IMC method yielded Kc = 2.21, τ_I = 16 minutes, and τ_D = 3 minutes.

Before entering the tuning parameter values into the controller program for the pyrolysis equipment, the parameters must be transformed into the basic PID controller equation indicated in Equation (6) and (7).

$$u(t) = Kc\left(e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt + \tau_D\,\frac{d\,e(t)}{dt}\right) \quad (6)$$

$$u(t) = KP\ e(t) + KI\ \int_0^t e(t)dt + KD\,\frac{d\,e(t)}{dt} \quad (7)$$

The Kc value is KP, the KI value is KP divided by τ_I, and the KD value is KP multiplied by τ_D. The CC approach yielded a KP value of 4.35; KI 0.28; and KD 11.30, whereas the IMC method yielded a KP value of 2.21; KI 0.14; and KD 6.64.

The controller program uses the tuning parameter values from each method to set the setpoint (SP1) at 200˚C. Once a steady state variable process value (PV1) is attained, the system servo changes to the new setpoint (SP2). At a temperature of 220˚C, a steady state variable process value (PV2) is achieved. The CC approach results in PV1 of 183˚C and PV2 of 209˚C, while the IMC method yields PV1 of 193˚C and PV2 of 213˚C.

The Cohen-Coon (CC) and Internal Model Control (IMC) tuning methods were applied to the derived FOPDT model, yielding the parameters shown in Table 1. The model-based IMC method provided a significantly more conservative gain (Kc=2.21) compared

to the aggressive CC setting (Kc=4.35), reflecting the ability of IMC to better manage the large dead time. The tuning results of each approach are then assessed for the controller's response characteristics using the parameters overshoot, t_r, t_s, and offset to find the method with the best controller characteristics. A good controller has low overshoot value, t_r, t_s, and offset. The overshoot parameter is calculated as the ratio of the maximum deviation from the final steady-state value (A=PVpeak−PVss) to the magnitude of the step change (B=PVss−PVinitial). A clear schematic representation for the calculation (Overshoot=A/B) is included. Figures 2 and 3 show the characteristic response curves for the CC and IMC methods, respectively.

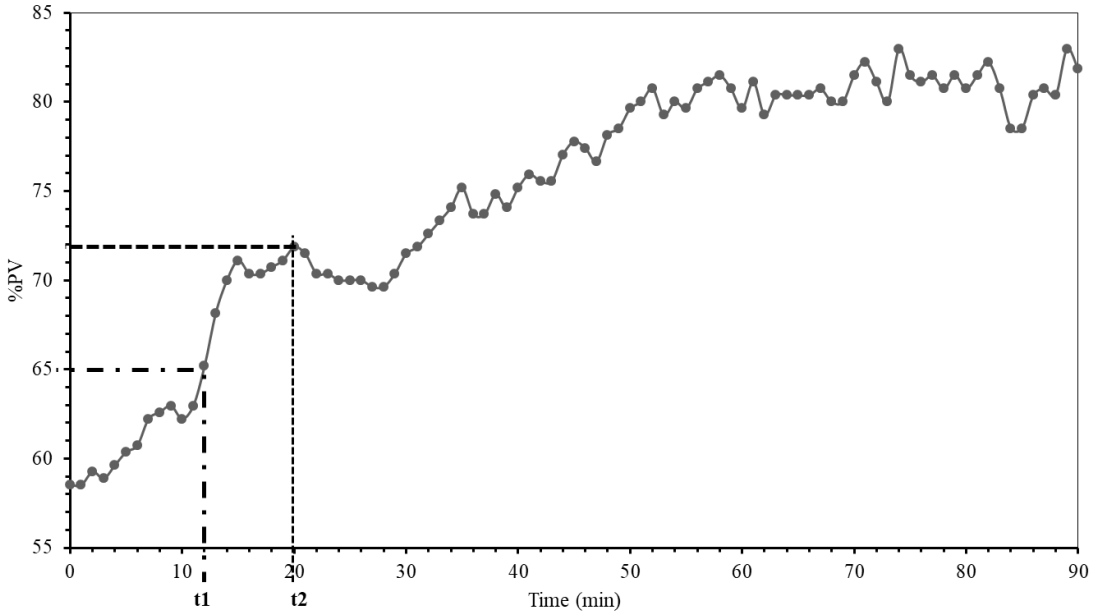

Figure 1. Response curve for estimating the transfer function of pyrolysis process.

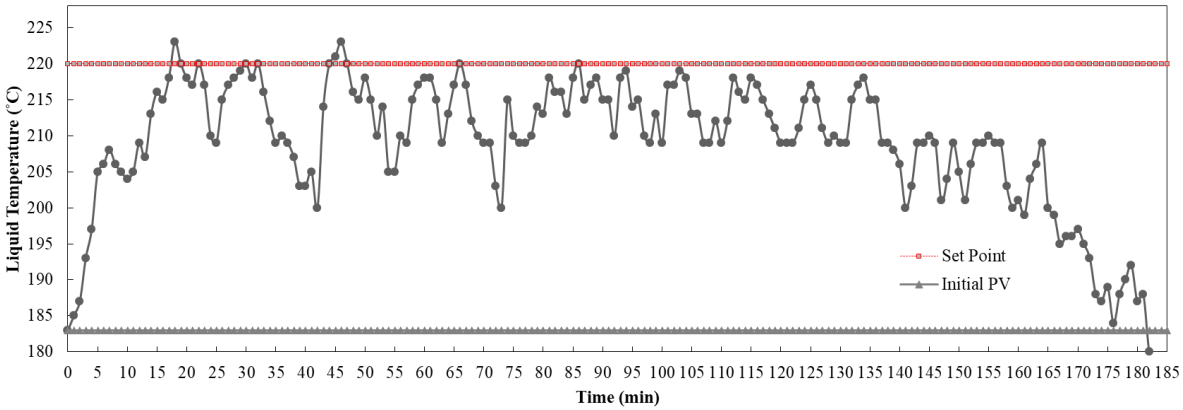

Figure 2. Characteristic response curve of the CC method.

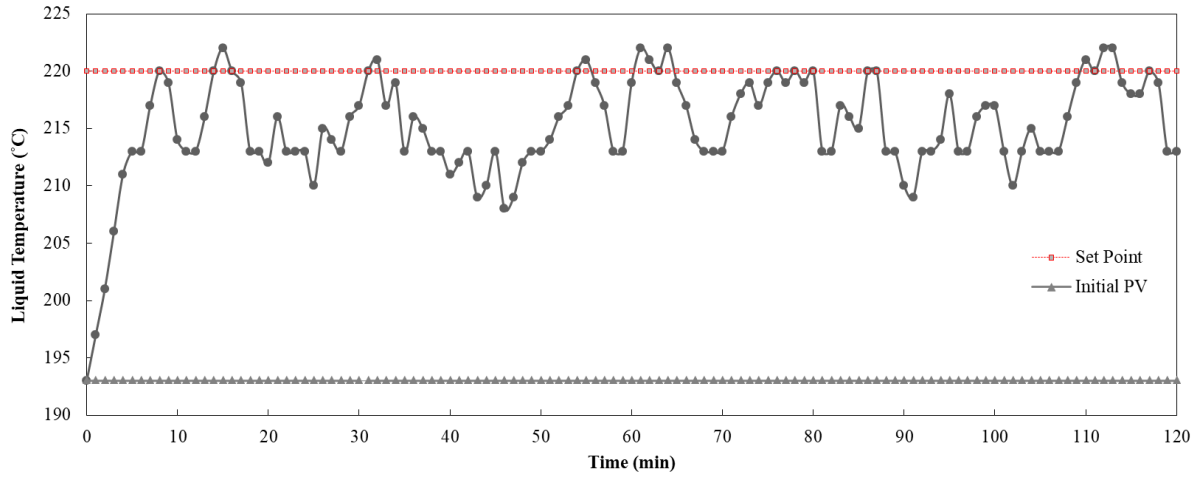

Figure 3. Characteristic response curve of the IMC method.

Table 1. Comparison of tuning responses using the CC method and the IMC method.

Operating Condition	Response	CC Method			IMC Method		
		KP	KI	KD	KP	KI	KD
		4.35	0.28	11.3	2.21	0.14	6.64
220˚C, 5 hours	Overshoot	0.5384			0.45		
	Rise time (t_r)	19 min			8 min		
	Settling time (t_s)	116 min			114 min		
	Offset	11˚C			7˚C		

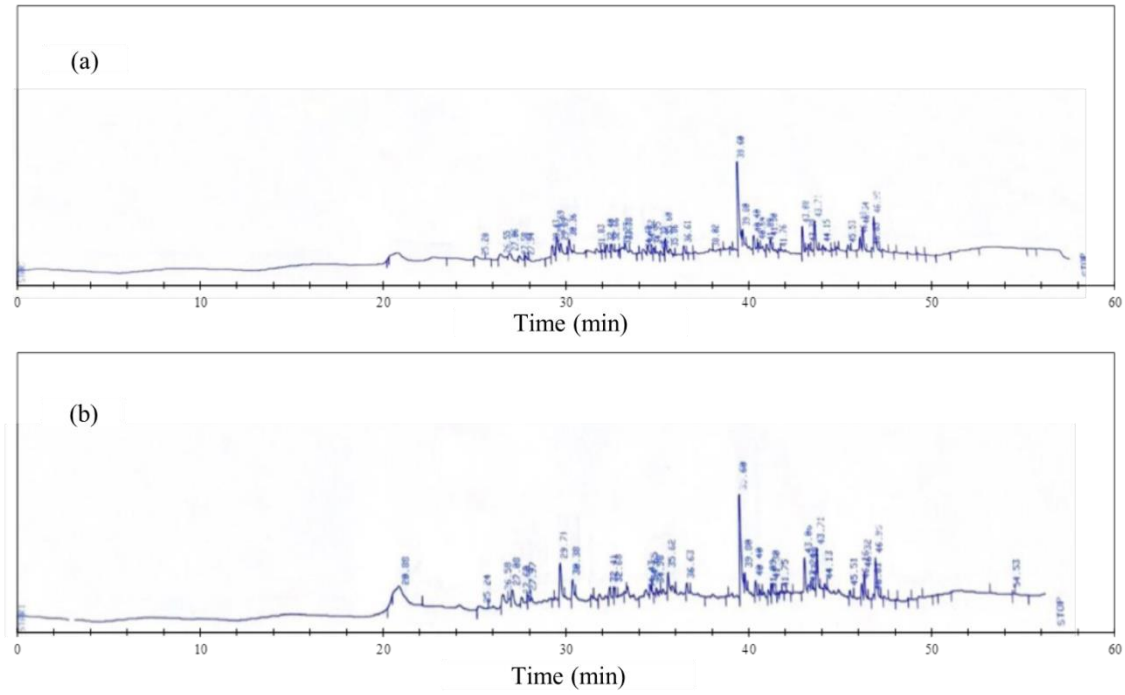

Figure 4. GC-FID Chromatogram of liquid product at (a) 220°C and (b) 250°C.

Table 1 and Figures 2-3 show that the IMC-tuned controller demonstrated superior transient response characteristics. The CC method exhibited a high overshoot (0.5384) and a larger steady-state offset (11°C). In contrast, the IMC method yielded a low overshoot (0.45), a faster rise time (8 min vs. 19 min), and a minimal offset (7°C),

confirming that the model-based IMC approach effectively compensated for the reactor's dead time, resulting in a more accurate and stable isothermal condition. This stability is the key technical enabler for product quality in the subsequent step.

3.2. Impact of Control Stability on Liquid Fuel Product

The enhanced stability provided by the IMC-tuned PID controller was fundamental to optimizing the liquid product quality at 250°C. The minimal temperature overshoot (0.45) and rapid settling time (114 min) ensured the feedstock was exposed to precisely isothermal conditions, minimizing non-selective secondary cracking which is detrimental to fuel quality.

3.2.1. Product Yield Distribution

The total liquid yield increased significantly with temperature (from 20.02% at 220°C to 28.55% at 250°C). More importantly, the valuable liquid fuel fraction yield also increased (from 11.83% to 14.45%). Concurrently, the fuel quality improved: density and viscosity increased from (778.6 kg/m^3 and 1.334 cSt at 220°C) to (785.8 kg/m^3 and 1.546 cSt at 250°C).This trend is consistent with the general principle of polymer cracking: higher temperatures promote chain scission, thereby increasing the release of volatile fractions that condense into liquid products. Similar observations were reported by Park, et al. (2021), who demonstrated that increasing pyrolysis temperature enhances liquid fuel yield during PP pyrolysis [13].

In addition to yield, the proportion of aqueous-like and cloudy by-products decreased at 250°C, suggesting more efficient conversion of polymeric feedstock into hydrocarbon-rich fractions. This behavior indicates that 250°C may represent a more favorable operating condition for maximizing the liquid fuel fraction in low-temperature pyrolysis of medical masks.

At 220°C, the fuel exhibited a density of 778.6 kg/m³ and viscosity of 1.334 cSt, while at 250°C, density and viscosity increased to 785.8 kg/m³ and 1.546 cSt, respectively. These values closely approximate those of kerosene (789 kg/m³, 1.61 cSt).

The increasing density and viscosity at higher temperature suggest that higher pyrolysis severity favored the formation of heavier hydrocarbons within the kerosene–diesel range. This is in line with the report of Talwar, et al. (2025), who reported that pyrolysis at higher temperatures enhances secondary cracking reactions, producing denser and more viscous fuels [28]. The close similarity to kerosene properties underscores the potential of pyrolysis oil from medical masks as a viable substitute for conventional middle distillates.

The qualitative observation results provide a qualitative comparison of pyrolysis fuel with conventional fuels. Qualitative observation indicated that the 250°C liquid fuel had a lighter color and a less pungent odor compared to the 220°C product, marginally resembling commercial kerosene. At 220°C, most panelists described the color of the fuel as darker than kerosene, while at 250°C, 60% of respondents classified the color as nearly identical to kerosene. Odor perception followed a similar pattern, with 48% of panelists indicating similarity to kerosene at 250°C.

These results suggest that increasing pyrolysis temperature not only enhances fuel yield but also improves its sensory resemblance to commercial kerosene. This observation is important in practical applications, as color and odor can influence fuel acceptance in domestic and industrial markets.

3.2.2. Hydrocarbon Composition (GC-FID)

GC-FID analysis (Figure 4) confirmed that the liquid fuels contained hydrocarbon fractions predominantly in the range of C9−C20. Retention times corresponding to major groups in commercial kerosene (C9−C16) and diesel (C15−C20) were identified, underscoring the potential for middle distillate substitution [29]. The

improved precision and yield at 250°C is directly traceable to the IMC controller's ability to minimize temperature excursions, thus preserving the desired C9−C20 product slate from non-selective thermal degradation. Notably, retention times between 29–39 min corresponded to major hydrocarbon groups also found in commercial kerosene and diesel standards.

These findings are consistent with the results of Sari, et al. (2024), who observed that medical mask pyrolysis generates hydrocarbon fractions spanning gasoline to diesel ranges. The presence of both kerosene- and diesel-like fractions in medical mask pyrolysis oil highlights its flexibility as a potential substitute for middle distillate fuels [29].

Overall, the integration of IMC-tuned PID control with pyrolysis not only improved system stability but also indirectly enhanced product quality and yield by maintaining isothermal conditions. The liquid fuels produced at 250°C exhibited properties highly comparable to kerosene, supported by density, viscosity, qualitative observation, and GC-FID results.

3.3. INDUSTRIAL IMPLICATIONS

From an industrial perspective, these results indicate that medical masks, a previously problematic waste stream, can be transformed into valuable energy resources. Furthermore, the implementation of optimized control strategies such as IMC-based PID ensures reproducible and stable operation, making the process more feasible for scale-up.

This study provides evidence that integrating process control with thermochemical conversion technologies can bridge the gap between laboratory research and practical waste-to-energy applications. The results contribute to the growing body of knowledge on plastic and medical waste valorization and may serve as a foundation for pilot-scale or industrial-scale development.

4. CONCLUSION

This study successfully validates the integration of advanced process control with pyrolysis for the effective valorization of medical mask waste into high-quality liquid fuel. Quantitatively, the Internal Model Control (IMC) tuning method provided superior performance, exhibiting a minimal overshoot (0.45) and a reduced steady-state offset (7°C) compared to the Cohen-Coon method. The IMC-tuned controller ensured stable isothermal conditions, which, when applied at 250°C, significantly enhanced the liquid fuel yield and product quality. The resulting liquid fuel exhibited properties highly comparable to commercial kerosene, with density 785.8 kg/m^3 and viscosity 1.546 cSt closely matching commercial standards, confirming the successful production of C9−C20 fractions. These findings underscore that precise, model-based control (IMC-PID) is the key technical enabler for achieving consistent, high-quality products in this waste-to-energy application. Future research should focus on utilizing FTIR for minor component analysis and, critically, on developing a continuous flow pyrolysis system to validate the IMC-PID control strategy under pilot-scale conditions for industrial feasibility.

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