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Proportional Integral Derivative Algorithm in Temperature Control of Plastic Waste Melting in Paving Block Making

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Abstract

Residual plastic waste is plastic that no longer has any commercial value and has a high potential to pollute the environment. One way to utilise it is to turn it into an adhesive to replace cement in the production of paving blocks by melting it together with used oil and construction sand. The melting temperature must be maintained at 250 °C–260 °C to achieve maximum adhesive strength and prevent material burnout. This study designed a temperature-control system for the melting of residual plastic materials during paving block production. The PID control algorithm was implemented as program code embedded in an Arduino Mega microcontroller. The performance of the control system was tested for four melting case studies with different material compositions. The control system's performance was also tested for reliability under changes in the temperature setpoint, from 100°C during initial heating to 250°C during final heating. The results show that the designed control system is capable of achieving the temperature value in accordance with the setpoint, with the number of oscillations ranging from 2-3 oscillations, overshoot of 4% - 11%, with a rise time between 3.5 - 4 minutes for a temperature setpoint of 100 °C and 5.5 - 7.5 minutes for a temperature setpoint of 250 °C. The control system is capable of following and adjusting to changes in the temperature setpoint, as required by the melting process.

INTRODUCTION

Plastic is one of the greatest inventions and has proven to be extremely versatile. Its lightweight, rust-proof, inexpensive, and reusable properties have made plastic very popular. Plastic is known as a material with a million uses [1]. Behind its popularity, plastic poses a very serious problem, particularly environmental pollution, due to the fact that plastic waste is very difficult to decompose in the soil [2]. Some plastic waste still has economic value and can be reused through a process involving specific technology to produce recycled plastic pellets [3]. These recycled plastic pellets are commonly used as raw materials for various other plastic-based products [4].

Some plastic waste no longer has economic value and is non-recyclable, better known as residual plastic waste. Types of plastic waste that fall into the residual category include used plastic bags, multilayer plastics such as sachets for various detergent and shampoo products, straws, instant noodle packaging, and the like [5]. The lack of economic value and low public awareness of waste sorting has the potential to cause pollution if disposed of directly into the environment [6]. This is because residual plastic waste is very difficult to decompose and takes tens to hundreds of years to break down [7].

The enormous production of plastic waste and awareness of environmental pollution have attracted global attention to research on the utilisation of plastic waste residues [8]. One technique for processing plastic waste is pyrolysis, a thermochemical recycling method. In the pyrolysis process, organic compounds (polymers) are heated at high temperatures (350 °C - 900 °C) to produce gaseous and liquid products consisting of paraffins, olefins, naphthenes, and aromatic compounds, as well as solid waste containing inorganic residues [9]. A study of plastic residues for asphalt modification through a dry mixing process, shredding and pelletising recycled plastic waste reduced the volume of asphalt required by 6% [10]. However, this process is not economically viable and also requires a large investment in technology. The use of plastic waste combined with construction sand as raw material in the production of paving blocks has been discussed in research [11]. Plastic residue as a binder replaces cement, making it more economical [12]. The composition of the materials and the melting temperature affect the strength of the moulded paving blocks.

PID is one of the most widely used control algorithms in industrial automation due to its reliability [13]. PID controllers are more dominant than other types of controllers and have been applied across the automotive, aviation, consumer electronics, medical, heavy equipment, chemical, and power systems industries [14][15]. The development of increasingly complex technology and industry has rendered classic PID less capable of controlling systems, leading to the development of digital PID implemented as program code embedded in programmable devices [16]. The control of brushless DC (BLDC) motors using microcontroller-based PID controllers is discussed in [17]. Research [18] presents PID control for the rotational speed of a DC motor drive in a mini-submarine. PID is also widely used to optimise the efficiency of thermal power generation systems by controlling temperature and water flow rate in steam generators [19]. Research [20] discusses the application of an Arduino-based PID controller for controlling the temperature in an HVAC testing laboratory. A similar study discussing the application of Arduino-based PID control algorithms to control the rotational speed of DC motors is presented in [21].

This research focuses on supporting technology for utilising residual plastic waste to replace cement as a binding material in the production of paving blocks. The basic material for making paving blocks uses a mixture of residual plastic waste, used oil, and construction sand. The technology automatically controls the temperature in the melting tank using a proportional-integral-derivative (PID) control algorithm. The temperature control system is designed to maintain the melting tube temperature within 250 °C – 260 °C to achieve maximum adhesive strength and prevent scorching. A prototype melting tank with a capacity of 5 litres was constructed. The composition of materials and the temperature setpoints were varied to test the control system's capability and performance. Setpoint changes were made to 100°C for the initial heating and 250°C for the final heating.

METHODS

The production of paving blocks from a mixture of plastic residue, oil, and construction sand consists of three main stages. The first stage is oil heating. At this stage, the oil in the melting tank is heated to 100°C and is ready to be mixed with the chopped plastic residue and construction sand simultaneously. The second stage is melting and mixing. At this stage, plastic waste is gradually added to the melting tank while stirring to ensure complete melting.

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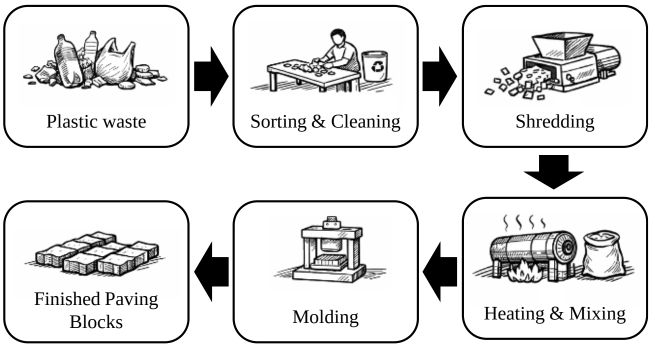

Figure 1. Production of paving blocks made from plastic residue, used oil, and construction sand.

Once the plastic has melted completely, sand is gradually added to the melting tank. Stirring continues to ensure that all materials are evenly mixed. This process continues until the temperature of the plastic-sand mixture reaches 260°C, at which point the mixture is ready for moulding. The third stage is the moulding of paving blocks. Figure 1 provides a comprehensive overview of the processing stages for residual plastic waste in the production of paving blocks.

PID Control Algorithm

PID (Proportional-Integral-Derivative) controllers consist of proportional, integral, and derivative controllers. The proportional controller (P) responds to the current conditions of a process output, the integral controller (I) responds to previous process outputs, and the derivative controller (D) predicts the response to the next process output [22]. The characteristics of PID controllers are strongly influenced by the contributions of the three controllers through the magnitudes of the control parameters/constants Kp, Ki, and Kd. Adjusting the values of Kp, Ki, and Kd will result in the dominance of each controller's characteristics. One or two of the three parameters can be set to be more dominant than the others. In PID control, the three controllers are combined in a series, parallel, or mixed structure to achieve optimal control system performance. This study uses a parallel PID structure as shown in Figure 2 [23].
The control output is calculated using the following equation (1).

$$u(t) = Kp\, e(t) + Ki \int e(t)dt + Kd \frac{de(t)}{dt} \quad \text{......(1)}$$

The result of the Laplace transform of equation (1) can be expressed as equation (2):

$$U(s) = \left(Kp + \frac{Ki}{s} + Kds\right) E(s) \quad \text{......(2)}$$

Based on equation (2), the transfer function of the parallel structure PID controller can be expressed in the following equation (3):

$$\frac{U(s)}{E(s)} = Kp + \frac{Ki}{s} + Kds \quad \text{......(3)}$$

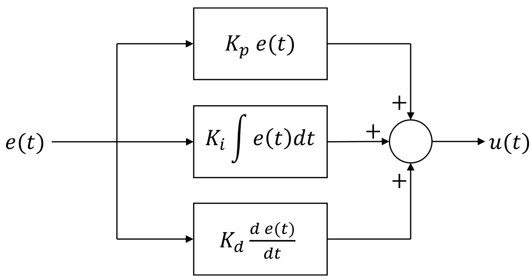

Figure 2. Parallel PID Block Diagram

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Figure 3. MLX-90614 temperature sensor integrated into the GY-904 module.

Table 1. Specifications of the MLX90614 and GY-906 temperature sensors

Model	GY-906
Power supply	5 Volt DC
Sensor	MLX90614
Operational temperature	-40°C to 125°C
Measurement range	-70°C to 380°C
Resolution	0,02°C
Material	Immersion Gold PCB

MLX-90614 non-contact temperature sensor integrated in the GY-906 Module

The MLX-90614 is a non-contact temperature detector that utilises infrared light for sensing [24][25]. The MLX-90614 is supported by an IR-sensitive thermopile detector chip integrated with a signal-conditioning amplifier circuit, a 17-bit ADC, and a DSP unit, providing high accuracy [26]. Its temperature detection range is -70 °C to 380 °C, with a resolution of 0.02 °C. Figure 3 shows the MLX-9016 sensor integrated into the GY-904 module. Table 1 shows the sensor specifications.

220 V 4000 W electric heating element

An electric heating element is a device that converts electrical energy into heat [27]. The amount of heat energy produced is proportional to the electrical energy supplied to the heating element [28]. In this study, the heating source used electric heating elements with specifications as shown in Table 2.

Heating Furnace and Melting Tank

The mechanics of the system consist of a heating furnace and a melting tank for plastic waste residue, as shown in Figure 4. The heating furnace uses a 220-volt electric heating element with a power capacity of up to 4000 watts. The heating element pad uses a ceramic material that is able to insulate heat. The melting tank has a capacity of 5 litres and is made of a 2 mm-thick iron plate.

Table 2. Heating element specifications

Tipe	Tubular
Bentuk	Spiral
Tegangan, daya	230 Volt, 4000 Watt
Diameter spiral	25 cm
Suhu pemanasan	Hingga 400 ºC

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(a) (b)

Figure 4. (a) Heating furnace, (b) Melting tank

Temperature Control System

The temperature control system is implemented by applying a PID algorithm integrated into the program code and embedded in the Arduino Mega microcontroller [29]. Figure 5 presents a block diagram of the overall system.

Based on Figure 5, the PID controller receives an error signal, which is the difference between the actual temperature measured by the sensor (the process variable, PV) and the desired temperature (the setpoint, SP). The PID controller processes the error value into a control signal, which is used as a manipulated variable (MV) to drive the dimmer circuit as a heating process actuator. The MV is a pulse-width modulation (PWM) signal that adjusts the heating level to keep the PV close to the SP. The performance of this control system is measured based on the system response in transient and steady-state conditions [15]. The application of the PID algorithm for temperature control in the smelting tank is shown in Figure 6.

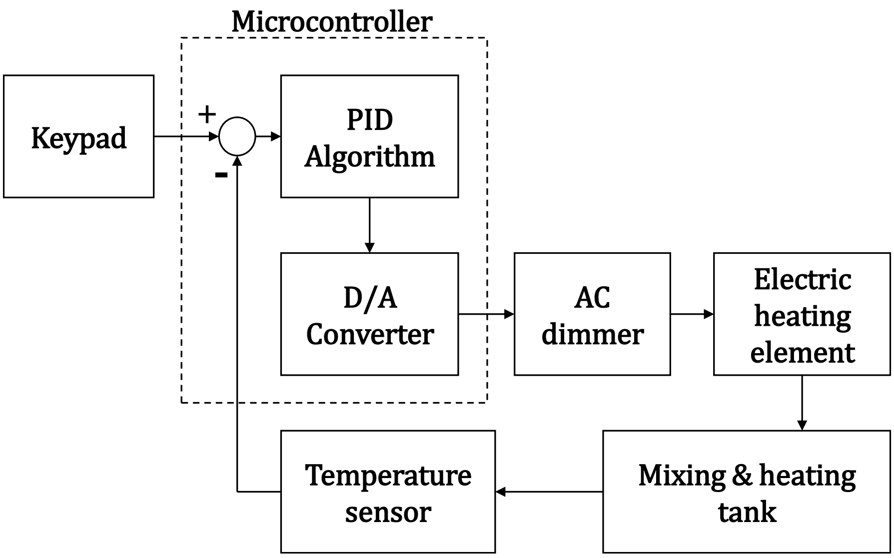

Figure 5. Block diagram of the control system

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```
Start
    Initialize error value: err ← 0
    Initialize last error value: last_err ← 0
    Initialize cumulative error value: accum_err ← 0
    Enter setpoint value: SP
    Set PID parameter values: Kp, Ki, and Kd
    While (true)
        Read temperature sensor output data as PV
        Determine the current error: err ← (SP – PV)
        Determine the change of error: d_err ← (err – last_err)
        Determine the accumulation of error: accum_err ← (accum err + err)
        Calculate the output of proportional: out_P ← (Kp * err)
        Calculate the output of integral: out_I ← (Ki * accum_err)
        Calculate the output of differential: out_D ← (Kd * d_err)
        Obtaine the output of PID: Out_PID ← (out_P + out_I + out_D)
        Update the last error: last_err ← err
    End while
End
```

Figure 6. Pseudo Code

Table 3. Detailed composition of materials for each temperature control system test case

Cases	**Material composition** (Used oil : Plastic : Sand)
Case 1	1.00 : 1.00 : 0.50
Case 2	1.00 : 1.00 : 0.75
Case 3	1.00 : 1.00 : 1.00

RESULT AND DISCUSSION

Temperature control testing was conducted across several case studies based on the materials used, as shown in Table 3. The composition was varied to obtain paving block mouldings with different strengths. In addition, this variation was also intended to test the control system's ability to control the temperature under various conditions with differences in the composition of materials used in the smelting process.

System response in test case 1

In test case 1, temperature control was performed on a material composition of 1 part oil, 1 part plastic, and 0.5 parts sand. This composition is equivalent to 400 grams of oil, 400 grams of plastic, and 200 grams of sand to obtain a total mixture weighing 1000 grams. The process began by heating the oil to a setpoint temperature of 100°C. At the end of the process, the temperature setpoint is increased to 250 °C for the melting process of plastic and construction sand. The temperature setpoint of 250 °C is maintained until all materials have melted evenly and are ready for moulding. Figure 7 shows the response of the temperature control system from the beginning to the end of the process.

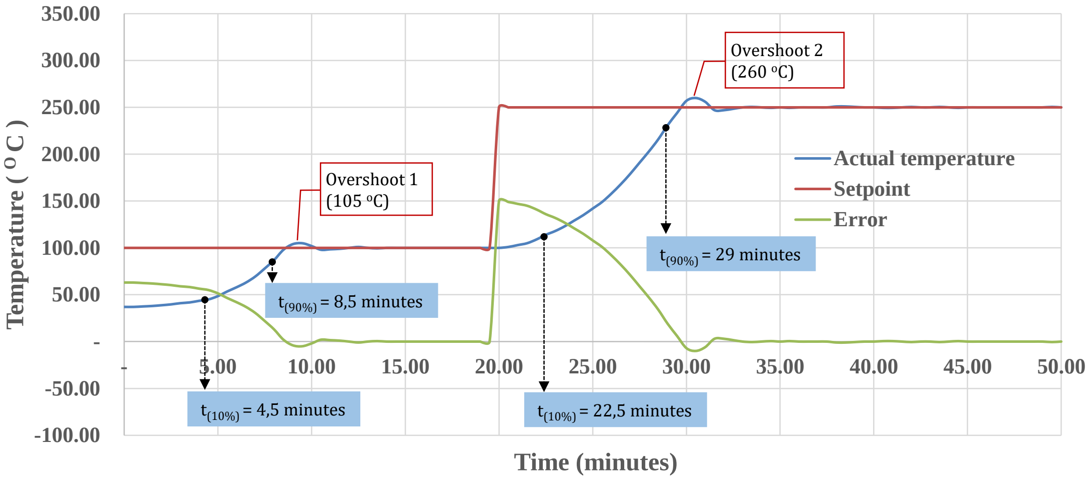

Figure 7. Response of the temperature control system in test case 1

At the start of the oil heating process, the initial temperature (T_{01}) is 37°C, and the temperature setpoint (T_{SP1}) is 100°C, so the total desired temperature change (ΔT) is 63°C. The oil temperature reaches 10% of ΔT in a time of $t_{10\%} = 4.5$ minutes, and reaches 90% of ΔT in a time of $t_{90\%} = 8.5$ minutes. The highest spike in oil temperature reaches 105°C, and the number of oscillations is twice.

The mixing and melting process of the materials is carried out with an initial temperature (T_{02}) of 100°C and a temperature setpoint (T_{SP2}) of 250°C. Thus, the desired temperature change (ΔT) is 150°C. During the melting process, the temperature in the melting tank reaches 10% of ΔT at 2.5 minutes and reaches 90% of ΔT at 9 minutes. This time is calculated from when the setpoint change is given at 20 minutes. The number of oscillations is twice, with the highest temperature reaching 260°C.

System response in test case 2

In test case 2, the composition of the materials consisted of 1 part oil, 1 part plastic, and 0.75 parts sand. This composition is equivalent to 364 grams of oil, 364 grams of plastic, and 273 grams of sand to obtain a total mixture weighing 1000 grams. The heating process is done in the same way as in case 1. In the oil-heating process, the setpoint is 100 °C. Meanwhile, in the melting process, the setpoint is set at 250 °C until all materials melt evenly and are ready for moulding. Figure 8 shows the response of the temperature control system from the beginning to the end of the process.

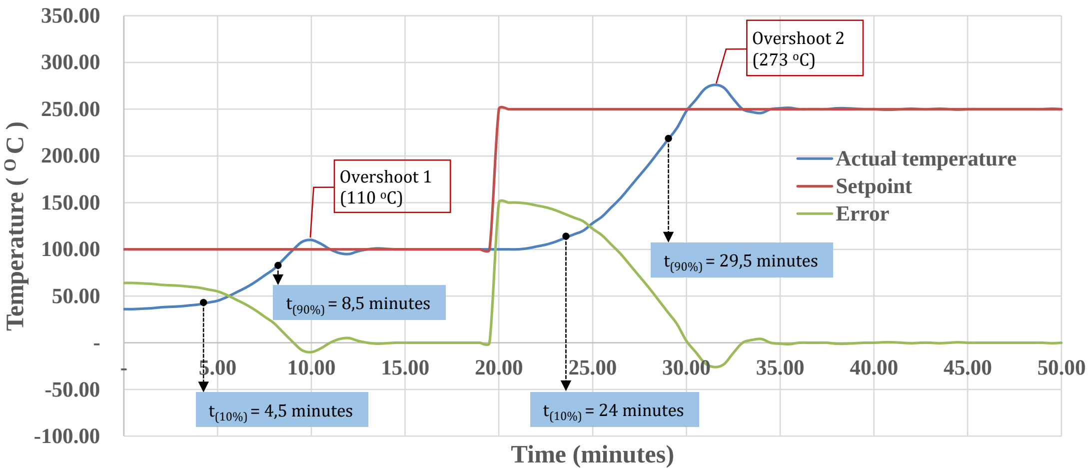

Figure 8. Response of the temperature control system in test case 2

Based on Figure 8, during oil heating, the initial temperature (T_{01}) is 36°C, and the setpoint is 100°C, with a total desired temperature change (ΔT) of 64°C. The oil temperature reaches 10% of ΔT at time $t_{10\%}$ = 4.5 minutes. The oil temperature continues to rise and reaches 90% of ΔT at time $t_{90\%}$ = 8.5 minutes. During heating, the highest temperature reaches 110°C and oscillates twice before reaching a steady state at 100°C.

Once the oil temperature reaches the setpoint of 100 °C, the mixing and melting process begins by changing the temperature setpoint to 250 °C at the 20th minute. Thus, the desired temperature change (ΔT) is 150 °C. The temperature in the melting tank increases by 10% of ΔT within 4 minutes of the setpoint change being applied. Meanwhile, a 90% increase in ΔT is observed 9.5 minutes after the setpoint change is applied. The number of oscillations is twice, with the highest temperature reaching 273 °C before stabilizing at 250 °C.

System response in test case 3

In test case 3, the testing procedure remained the same as before, but was applied to a material with a composition of 1 part oil, 1 part plastic, and 1 part sand. This composition is equivalent to 333 grams of oil, 333 grams of plastic, and 333 grams of sand, yielding a total mixture weighing 1000 grams. Figure 9 shows the response of the temperature control system from the beginning to the end of the process.

Based on Figure 9, the initial temperature (T_{01}) of the oil heating is 37°C and the setpoint (T_{SP}) is 100 °C, so the total desired temperature change (ΔT) is 63°C. The oil temperature reaches 10% of ΔT at time $t_{10\%}$ = 5 minutes and reaches 90% at time $t_{90\%}$ = 8.5 minutes. Before reaching a stable 100°C, the temperature oscillates twice, reaching a maximum of 111°C.

After the oil stabilised at 100°C, the setpoint was raised to 250°C at the 20th minute to continue the mixing and melting. The total temperature change was 150°C. During the melting process, the temperature in the melting tank reached a 10% increase from ΔT within 4 minutes and reached 90% of ΔT within 11 minutes from the time the setpoint change was applied. The temperature in the melting tank oscillated twice, with a maximum of 270°C.

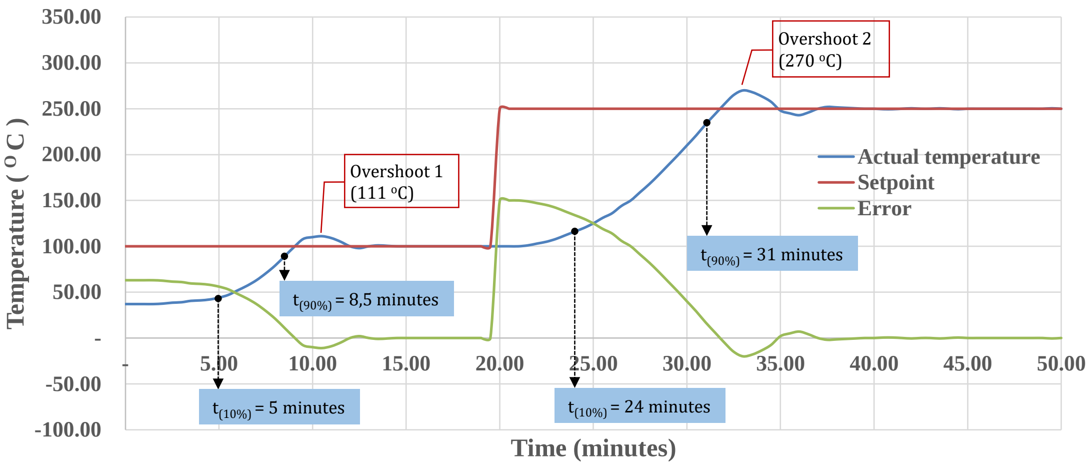

Figure 9. Response of the temperature control system in test case 3

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Discussion

The performance of a control system is assessed based on several parameters, including the number of oscillations, rise time, and overshoot. These parameters are determined based on the control system's response to setpoint changes given during the control process. The number of oscillations is the number of oscillations that occur from the time the setpoint change is given until the system reaches a steady state. Fewer oscillations indicate better control of process parameters. Rise time is the time required by the system from when the output reaches 10% to 90% of the given setpoint change. A shorter rise time indicates that the control system responds quickly to setpoint changes. Overshoot is the maximum deviation of the actual output value from the setpoint, expressed as a percentage (%). From testing three different case studies, the overall response of the control system can be summarised in Table 4.

Based on Table 4, the control system response results for the three case studies indicate that the control system can maintain the temperature within the setpoint range during the given setpoint changes. The first setpoint change was applied at the beginning of the process to 100 °C, and the second was applied during the melting process at 250 °C. The control system was able to track the temperature setpoint with rise times of 3.5–4 minutes for the first setpoint change and 5.5–7.5 minutes for the second setpoint change.

Table 4. Summary of control system responses for three different case studies

Test cases	**Parameters**		**Initial process** (Oil heating)	**Final Process** (Melting)
Case 1	Initial temperature (T_{01})	(ºC)	37	100
	Temperature setpoint (T_{SP})	(ºC)	100	250
	$\Delta T = T_{SP} - T_{01}$	(ºC)	63	150
	The actual temperature reaches 10% of ΔT ($t_{10\%}$)	(minute)	4,5	22,5
	The actual temperature reaches 90% of ΔT ($t_{90\%}$)	(minute)	8,5	29,0
	Number of oscillations		2	2
	Highest temperature (T_{max})	(ºC)	105,0	260,0
	Rise time = $t_{90\%} - t_{10\%}$	(minute)	4,0	6,5
	Overshoot = $\left(\frac{T_{max}-T_{SP}}{T_{SP}}\right)100\%$	(%)	5,0	4,0
Case 2	Initial temperature (T01)	(ºC)	36	100
	Temperature setpoint (TSP)	(ºC)	100	250
	ΔT = TSP - T01	(ºC)	64	150
	The actual temperature reaches 10% of ΔT ($t_{10\%}$)	(minute)	4,5	24,0
	The actual temperature reaches 90% of ΔT ($t_{90\%}$)	(minute)	8,5	29,5
	Number of oscillations		2	2
	Highest temperature (Tmax)	(ºC)	110	273
	Rise time = $t_{90\%} - t_{10\%}$	(minute)	4,0	5,5
	Overshoot = $\left(\frac{T_{max}-T_{SP}}{T_{SP}}\right)100\%$	(%)	10,0	9,2
Case 3	Initial temperature (T_{01})	(ºC)	37	100
	Temperature setpoint (T_{SP})	(ºC)	100	250
	$\Delta T = T_{SP} - T_{01}$	(ºC)	63	150
	The actual temperature reaches 10% of ΔT ($t_{10\%}$)	(minute)	5,0	24,0
	The actual temperature reaches 90% of ΔT ($t_{90\%}$)	(minute)	8,5	31,0
	Number of oscillations		2	2
	Highest temperature (T_{ma}x)	(ºC)	111	270
	Rise time = $t_{90\%} - t_{10\%}$	(minute)	3,5	7,0
	Overshoot = $\left(\frac{T_{max}-T_{SP}}{T_{SP}}\right)100\%$	(%)	11,0	8,0

The rise time was also strongly influenced by the controlled process's response characteristics. In thermal systems with a heating process for solid materials, there is a tendency toward slow response.

During transient conditions when the actual temperature has not yet reached a stable state relative to the setpoint, oscillations occur in the actual temperature. The number of oscillations across the entire test shows relatively similar results, ranging from 2 to 3. This indicates that the control system can dampen oscillations so they do not persist for long, and the temperature output immediately reaches a stable value in accordance with the given setpoint.

During transient conditions, the actual temperature surge exceeds the setpoint value. In control systems, this condition is better known as overshoot. The overshoot observed throughout testing ranged from 4% to 11%. The overshoot value is also influenced by the sampling time used. As mentioned earlier, thermal processes have a slow response, so the sampling time must be adjusted to the controlled process's response speed. In the tests conducted in this study, a sampling time of 30 seconds was used.

CONCLUSION

A temperature control system for the melting process of paving blocks made from plastic waste residue as a binding material has been developed using a PID control algorithm implemented on an Arduino Mega microcontroller. The performance of the temperature control system was tested for four melting case studies with variations in the composition of plastic, oil, and building sand. Changes to the temperature setpoint were made in accordance with the process requirements. The performance of the PID controller was measured based on system response parameters, including rise time, number of oscillations, and overshoot. Overall, the control system design with the PID algorithm showed satisfactory results in controlling the temperature in the melting process of paving block production materials. The control system was able to follow and adjust to changes in the temperature setpoint, as specified by the melting process stages.

As a further project, research was conducted on pressure control systems for paving block moulding machines. This resulted in a complete system package for processing plastic waste into paving blocks, from melting to moulding. The control system was also developed by applying fuzzy logic as a comparison to the PID control system, and by hybridising the two existing control algorithms.

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