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Improved Design and Fabrication of a Compression Moulding Machine with Performance Evaluation

Ojo. A. A., Olanipekun K. A., Omoniyi J. O., Akinsipe A., Ilesanmi R. I.
Department of Mechanical Engineering, Ekiti State University, Ado Ekiti, Nigeria.
chartell2006@yahoo.com

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Abstract: *This study explores the advancements in the design and performance of an improved compression moulding machine aimed at efficiently recycling various plastic wastes, with an emphasis on Polyethylene Terephthalate (PET). With global plastic waste accumulation posing severe environmental challenges, enhancing recycling technologies is imperative. The re-designed machine was tested at operating temperatures of 200°C, 250°C, and 300°C, highlighting the critical role of temperature and processing duration in determining product quality. Theoretical heating times were found to be shorter than actual times due to real-world inefficiencies such as heat loss and thermal conductivity variations. Weight loss during heating, attributed to the evaporation of volatile components and thermal degradation, was observed. The formation of air pores in samples with extended heating times underscored the necessity for precise process control. The PET melting process initiated effectively at approximately 250°C. The improved machine demonstrated significant potential in enhancing recycling efficiency and versatility.*

Keywords: plastic recycling; compression moulding; polyethylene terephthalate (PET); thermal degradation; sustainable waste management; environmental Impact

INTRODUCTION

With the steady increase in global population comes commensurate increase in waste from the by-products of the necessities to service the populace. The accumulation of waste materials, particularly plastic waste, has outpaced the ability to handle plastic waste effectively and this has become a significant environmental challenge in recent decades. Plastics, owing to their durability and resistance to degradation, persist in the environment for extended periods, leading to severe ecological impacts. Improper disposal, unmatched plastic waste management and the non-biodegradable nature of plastics contribute to pollution in terrestrial and marine ecosystems, adversely affecting wildlife and human health. Studies have shown that plastics can fragment into microplastics, which are ingested by marine organisms, entering the food chain and posing risks to larger animals and humans [1], [2]. Based on composition and treatment, plastics is made up of different types with varying characteristic properties. Common types include polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS) [3]. Recycling these plastics presents a complex challenge, but offers a crucial solution to mitigate plastic pollution. Various methods have been explored for recycling plastic waste, including mechanical recycling, chemical recycling, and thermal processes such as pyrolysis [3], [4] and compression moulding at high temperatures [5]. Mechanical recycling involves collecting, sorting, and processing plastics into new products. This method is widely used for materials like PET and HDPE but is limited by the quality of the recycled plastic, which often degrades with each cycle [6]. Chemical recycling breaks down plastics into their monomers or other valuable chemicals through processes like depolymerization, pyrolysis, and gasification. This approach can handle a broader range of plastics and produce higher-quality recycled materials. However, it requires significant energy input and complex infrastructure [7]. Pyrolysis is a thermal decomposition process conducted in the absence of oxygen, converting plastics into liquid fuels, gases, and char. This method can process mixed plastic waste and generate valuable by-products, but it faces challenges related to process optimization, energy efficiency, and by-product management [8]. Compression moulding involves applying heat and pressure to plastic waste to form new products. This technique is advantageous for its simplicity and ability to process a variety of plastic types. Previous studies have demonstrated the potential of compression moulding for recycling plastics into useful items, but further improvements in machine design and process efficiency are necessary to enhance its viability. Despite advancements in plastic recycling technologies, there is a need for improved machinery that can handle diverse plastic waste efficiently and sustainably. Current machines often lack the structural integrity, material handling capabilities, and process flow optimization required for effective recycling. While these methods hold promise, there remains a gap in optimizing plastic recycling machines for efficiency, throughput, and versatility.

Therefore, this work aims to modify the design and fabricate a more robust compression moulding machine, incorporating improvements in its efficiency, throughput, and versatility. This includes optimizing the machine's structural integrity, material handling capabilities, and process flow to accommodate various types of plastic waste and maximize recycling efficiency.

MATERIALS AND METHOD

The improved compression moulding machine was meticulously designed to accommodate the specific temperature needs of different plastic types, as each plastic has a unique melting point. Understanding these differences is crucial, as improper temperatures can compromise the quality of the plastics. Therefore, a significant portion of the design process involved researching the thermal properties of various plastics. The machine's heating mechanism was also carefully considered, focusing on the heater's configuration to ensure efficient and consistent operation. Additionally, a thermostat was included to continuously monitor and adjust the temperature, ensuring that plastics are always processed at their optimal temperatures. This guarantees the production of high-quality moulded items.

Major Design Consideration and Analysis

Furnace Dimensions
External surface of the Heating Chamber

$$Outer\ Length\ (l_o) = 0.66\ m$$

$$Outer\ Breath\ (b_o) = 0.66\ m$$

$$Outer\ Heigth\ (h_o) = 0.635\ m$$

$$Outer\ Casing\ Volume\ (V_o) = l_o \times b_o \times h_o = (0.66 \times 0.66 \times 0.635)\ m^3 = 0.2766\ m^3$$

Internal surface of the Heating Chamber

$$Inner\ Length\ (l_i) = 0.6348\ m$$

$$Inner\ Breath\ (b_i) = 0.6348\ m$$

$$Inner\ Height\ (h_i) = 0.6098\ m$$

$$Inside\ Casing\ Volume\ (V_i) = Heating\ Chamber\ Volume = l_i \times b_i \times h_i$$

$$= (0.6348 \times 0.6348 \times 0.6098)\ m^3 = 0.2457\ m^3$$

$$Heating\ Chamber\ Surface\ Area\ (A_c) = 2[(l_i \times h_i) + (h_i \times b_i) + (l_i \times b_i)]$$

$$= 2[(0.4030) + (0.3871) + (0.3871)]\ m^3 = 2.3544\ m^2$$

$$Chamber\ Perimeter\ (P_c) = 2(l_i + b_i) = 2(0.6348 + 0.6348) = 2.5392\ m$$

1.1.1 Mould Dimensions (Female)

$$Inner\ Length\ (l_{ifm}) = 0.5836\ m$$

$$Inner\ Breath\ (b_{ifm}) = 0.5754\ m$$

$$Height\ Height\ (h_{ifm}) = 0.0746\ m$$

$$Female\ Mould\ Inner\ Casing\ Volume\ (V_{ifm}) = l_i \times b_i \times h_i$$
$$= (0.5836 \times 0.5754 \times 0.0746)\ m^3 = 0.0251\ m^3$$

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1.1.2 Heating Rate and Heating Element

For Plastic

$$Given\ the\ maximum\ mass\ of\ plastic\ (m_p) = 0.1\ kg$$

$$Change\ in\ temperature\ (\Delta T) = 498K - 298K = 200\ K$$

$$Specific\ heat\ capacity\ of\ the\ plastic\ (c_p) = 2400\frac{J}{kg\ K}$$

$$Energy\ required\ for\ the\ plastic\ (Q_p) = m_p \times c_p \times \Delta T$$

$$= 0.1 \times 2400 \times 200 = 48000\ J = 4.8 \times 10^4\ J$$

For Mould

$$Given\ the\ maximum\ weight\ of\ Mould\ (m_m) = 3.5\ kg$$

$$Change\ in\ temperature\ (\Delta T) = 200\ K$$

$$Specific\ heat\ capacity\ of\ the\ mold\ (c_m) = 460\frac{J}{kg\ K}$$

$$Energy\ required\ for\ the\ plastic\ (Q_m) = m_m \times c_m \times \Delta T$$

$$= 3.5 \times 500 \times 200 = 350000\ J = 3.5 \times 10^5\ J$$

Total Energy Required

$$Q_{Total} = Q_p + Q_m = 48000\ J + 350000\ J = 398000 = 3.98 \times 10^5\ J$$

Heating Rate

Given the heating capacity of the heating element (P) is 750 W (watts), the time (t) required to supply the total energy (Q_{total}) can be calculated as

$$t = \frac{Q_{total}}{P} = \frac{3.98 \times 10^5\ J}{750\ W} = 530.6\ s = 9.34\ min$$

The improved compression moulding machine comprises of a simple arrangement consisting of a lagged heating chamber with an access door having a transparent tempered glass framed and a two layered rigid metallic frame as shown in Figure 1. The heating chamber mounted on a rigid metallic frame houses a heater, rigid male mould, moveable female mould and a flat-

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top compression push rod aligned under the female mould. Underneath the heating chamber and aligned with the push rod which is a hydraulic jack connected to the push rod. The heating parameters such as heating temperature and duration is regulated using the electric controller with fitted thermocouple. The heat controller is mounted on the lower layer of the main frame.

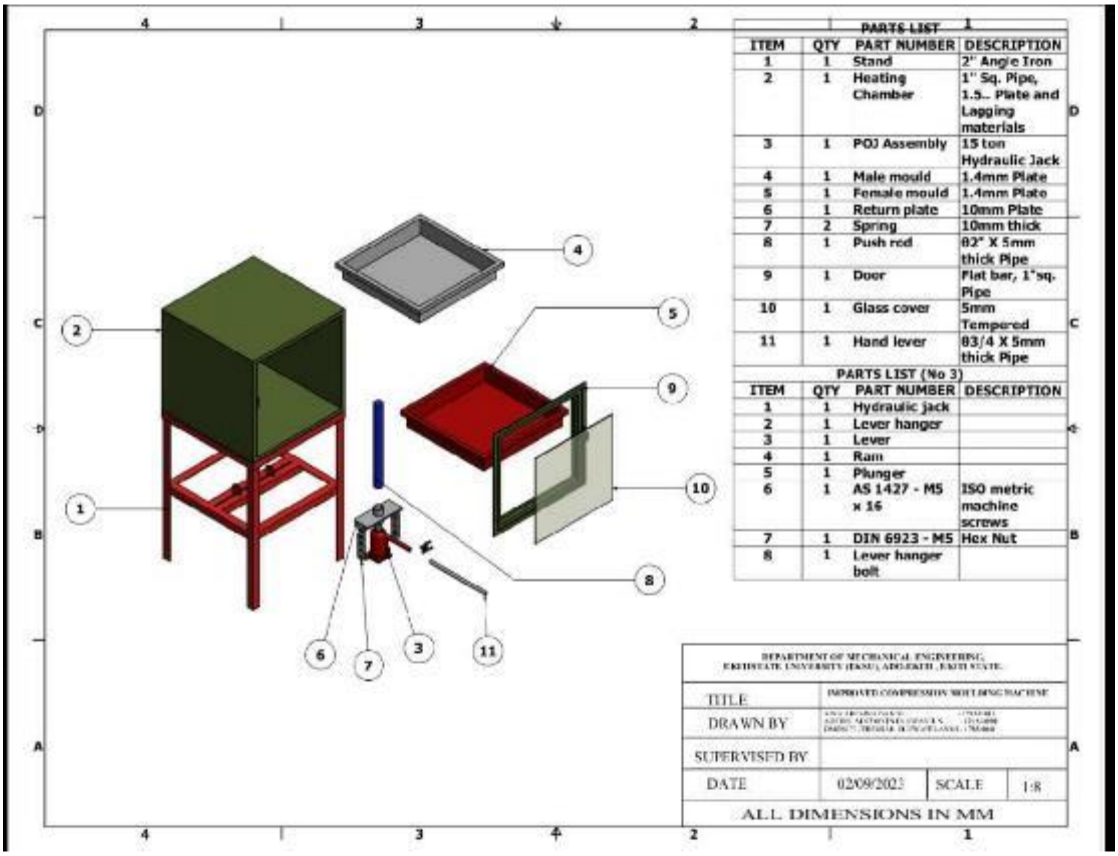

Figure 1: Exploded view of the improved compression moulding machine.

Principle of Operation

The improved compression moulding machine as shown in Figure 2 operates by heating and compressing plastic materials within a controlled environment. The process begins with

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Figure 2: Improved compression moulding machine

placing the plastic material into the moveable female mould inside the heating chamber. The heater, regulated by an advanced electric controller and thermocouple, warms the chamber to the required temperature, ensuring the plastic reaches its optimal melting point. Once the plastic is adequately heated, the hydraulic jack activates, pushing the flat-top compression rod against the female mould. This compresses the molten plastic into the desired shape, held in place by the fixed male mould. After the moulding process, the chamber cools down, allowing the newly formed product to solidify and be safely removed.

RESULTS AND DISCUSSION

The performance evaluation of the improved compression moulding machine was conducted using different types of plastics across various batches, including combinations of different plastics. Particular emphasis was placed on Polyethylene terephthalate (PET) due to its abundance in the locality. The effect of operating temperature, the temperature retention time were examined. The evaluation explored three operating temperatures: 200°C, 250°C, and 300°C with a temperature hold time of 300 s at the set temperature (see
). As the change in temperature (ΔT) increases from 200 K to 275 K, the total energy required to heat the plastic and mould rises from 182420 J to 260952.5 J respectively. Consequently, the estimated heating times increase from 4.1 minutes to 5.8 minutes as shown in
1 and Figure 3.

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Table 1: Table of the running temperature and the time required to reach the operating temperature.

Chamber Temp. (K)	Change in Temp. T_2-T_1 (K)	Energy Required for Plastic Q_p (J)	Energy Required for Mould Q_m (J)	Total Energy Required Q_{Total} (J)	Estimated Time Required *t* (min)	Measured Time Required *t* (min)	Weight (kg)
498	200	21420	161000	182420	4.1	7.2	100
523	225	24097.5	184500	208597.5	4.6	8.6	99.1
548	250	26775	208000	234775	5.2	11.0	98.5
573	275	29452.5	231500	260952.5	5.8	18.1	96.4

However, the measured times are consistently higher, ranging from 7.2 minutes to 18.1 minutes. This discrepancy highlights real-world factors such as heat loss, lower heating element efficiency, and uneven thermal conductivity, which are not accounted for in the theoretical calculations. The gap between estimated and measured times widens with higher temperatures, indicating that these inefficiencies become more pronounced at higher heating requirements. Additionally, after the heating and molding process, the weight loss is observed from the initial 100g. This indicates weight losses can be attributed to the evaporation of volatile components, thermal degradation, and/or hydrolytic process of the plastic material

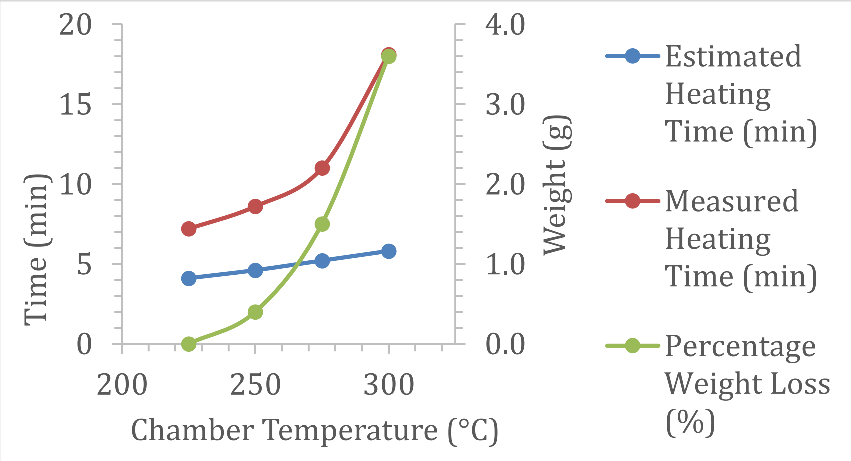

Figure 4: Graph of time taken against chamber temperature and sample weight.

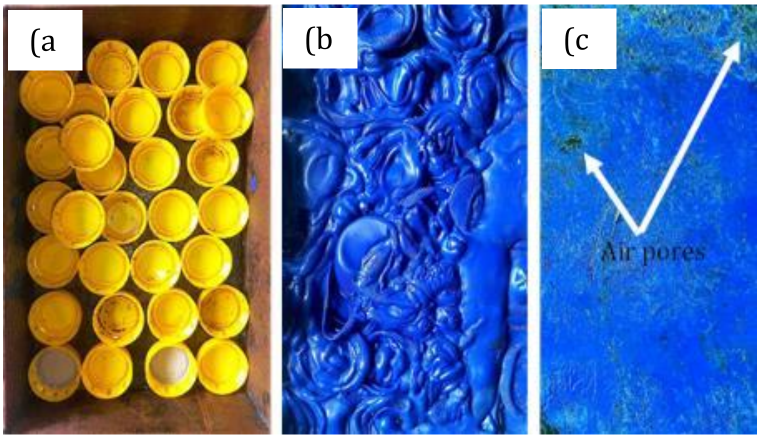

Figure 3: Waste PET from bottle cap (a) pre-processed sample, (b) post-processed sample at 250°C for 5 minutes (c) post-processed sample at 250°C for 10

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during the heating and moulding process. Further observation of the samples revelled that the PET melting was triggered at around 250 °C and that time taken for the melting and compression process is crucial. This is evident in Figure 4 which depicts the waste PET under (a) pre-processed condition, (b) post-processed sample at 250°C for 5 minutes (c) post-processed sample at 250°C for 10 minutes.

As expected, the high energy demand was observed for higher temperature retention time as depicted in Figure 5. Additionally, the development of air pores is observed after foe samples with retention time of 10 minutes and above which increases with the time (see Figure 4(c)). The presence of air pores and traps might be due to the evaporation of volatile components.

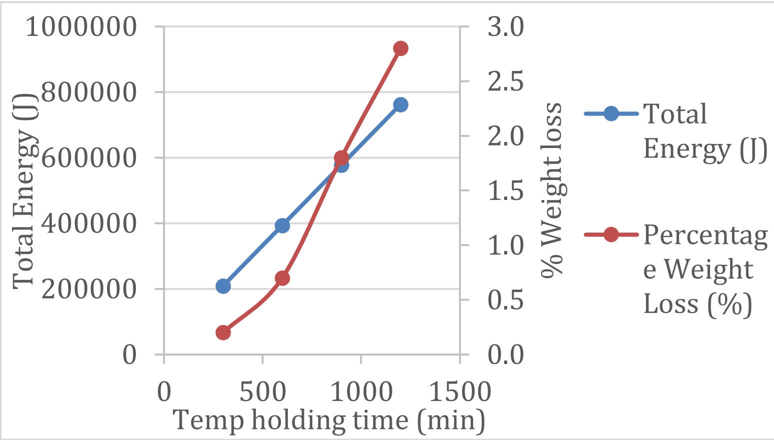

Figure 5: Graph of temperature holding time against the Total Energy and the Percentage weight loss.

The comparison of the improved compression moulding machine with the existing moulding machine is itemised in Table 2.

Table 2 Comparison of the existing and improved Machines

S/N	Existing Compression Moulding Machine	Improved Compression Moulding Machine
1	Bulky	Small
2	Low temperature range (30-120 ^{0}C)	Higher temperature range (30 - 350 ^{0}C)
3	Longer processing time per batch (5 to 7 hours)	Reduced processing time per batch (60 minutes)
4	Lower production rate - maximum of 2 samples per day	Higher production rate - 1 sample per hour
5	Low compression force -less than 1 ton	Higher compression force – up to of 10 tons
6	High energy consumption rate electric	Energy conserved electric element with higher heating rate

7	Many parts	Reduced components
8	Suitable for melting and moulding of Polyethylene (HDPE and LDPE) plastics only.	Suitable for melting and moulding of Polyethylene, Polypropylene, Polyvinyl Chloride, Polystyrene, Polyethylene terephthalate and Polyurethane plastics

CONCLUSION

This study evaluated the performance of an improved compression moulding machine for processing various plastic wastes, with a focus on Polyethylene Terephthalate (PET). Operating temperatures of 200°C, 250°C, and 300°C were tested, highlighting the importance of temperature and duration on product quality. While theoretical heating times were shorter than measured times due to real-world inefficiencies like heat loss and material thermal conductivity, they provided a useful benchmark for energy requirements. Weight loss observed during heating, attributed to the evaporation of volatile components and thermal degradation, necessitates careful management to maintain material integrity. The development of air pores in samples with prolonged heating emphasizes the need for precise process control. PET melting was effectively initiated at around 250°C, with process duration being crucial for quality. The enhanced machine design shows promise in improving plastic recycling efficiency and versatility. Future work should focus on optimizing heating mechanisms and reducing heat loss to further enhance material properties and recycling efficiency, contributing to sustainable waste management practices.

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Conflict of Interest

Authors would like to thank Engr. Henry Benjamin (ABUAD) for providing the technical contributions made to this work.

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