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Thermo-Economic Assessment of Heating Section Configurations in a Plastic Recycling Extruder

A.A. Okon[1], K.L. Usoro[2,] D.A. Jacob[3], I.O. Asuquo[4], A.E. Uyah[5]

[1, 2, 3, 4, 5]*Department of Mechanical and Aerospace Engineering, University of Uyo, Nigeria.*

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ABSTRACT: This study evaluates the thermal performance and economic impact of alternative heating-section designs in a single-screw plastic recycling extruder. Three configurations were compared: (1) the conventional baseline with exposed band heaters, (2) a baseline modified with a fibreglass insulation wrap, and (3) a baseline enclosed in a silicon carbide composite shell. Detailed CFD and heat-transfer simulations were conducted to predict temperature profiles and heat losses in each case. The analysis shows that applying insulation significantly reduces convective losses and improves temperature uniformity – for example, fibreglass wraps increased heating efficiency by about 42% and SiC enclosure by about 29% compared to the uninsulated baseline. These thermal gains translate into lower electrical energy demand and cost. A simplified economic model, using typical energy prices and operational hours, indicates that the improved configurations yield substantial annual energy savings and pay for themselves within a few years. The results demonstrate that thoughtful thermal design in extruder heating sections can meaningfully cut energy waste and operating expense in plastic recycling.

KEYWORDS: Insulation, Energy Efficiency, Heat Transfer, Economics, Thermal Performance

I. INTRODUCTION

In this paper, three configurations of the heating section in a plastic recycling extruder are examined. The first configuration represents the baseline case with exposed band heaters; the second adds a fibreglass insulation wrap around the heater bands; and the third encloses the barrel and bands within a silicon-carbide composite shell. Through computational simulations, we analyse temperature distributions, heat fluxes, and system response times for each scenario. By translating thermal performance into significant energy consumption metrics, we develop a simplified economic model to estimate annual operating costs and potential savings.

The objective of this study is to provide a comprehensive thermo-economic assessment of heating section designs, demonstrating how relatively simple insulation modifications can enhance thermal efficiency and reduce energy expenditures. By quantifying both heat retention improvements and corresponding cost implications, we offer practical insights for extruder manufacturers and recycling facilities seeking to optimise their processes. The results underscore the importance of thermal management in extrusion and lay the groundwork for future exploration of integrated energy-saving strategies. These findings contribute to the pursuit of sustainable manufacturing practice.

[1]. In plastic recycling, the extrusion process plays a central role in transforming waste polymers into reusable materials. The extruder's heating section is particularly critical, as it provides the thermal energy required to melt and convey plastic feedstocks. Conventional extruders typically employ band heaters applied directly to the barrel, resulting in substantial heat loss to the environment. These losses not only increase energy consumption but also elevate operational costs and carbon emissions. Improving the thermal design of the heating section can therefore yield significant benefits in terms of energy efficiency and economic performance.

[2]. Global plastic production has escalated dramatically since 1950, with over 8 billion tons produced and an estimated 6.3 billion tons discarded as waste.Unfortunately, only on the order of 9–12% of this plastic is recycled. The vast

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majority of waste plastics end up in landfills, incinerators, or pollute the environment, creating both economic loss and environmental harm. This situation has spurred increased interest in mechanical recycling processes to reclaim material value.

[3] In mechanical recycling, used plastics are typically sorted, shredded, melted, and reformed. The melt-processing step is usually performed by an extruder, which is essentially a screw-driven barrel that plasticizes and conveys the polymer. Because extrusion is energy-intensive, improving the efficiency of extruders is a key goal for sustainable recycling. Figures 1-5 depict a modern Plastic reduction machine and its key components, still with their limitations.

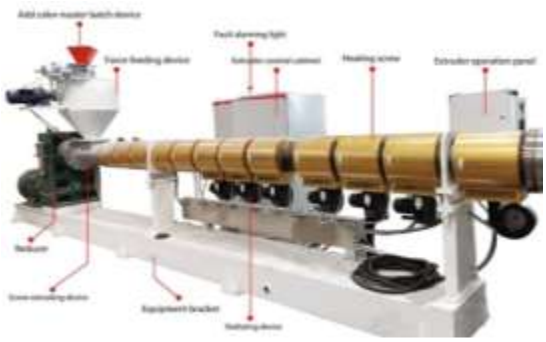

Figure 1: A Modern Plastic Reduction Machine

Figure 2: Extruder Heater Bands

Figure 3: Plastic Extruder Screw

Figure 4: Cylindrical Extruder Barrel

Figure 5: Fibreglass Thermal Insulation Wraps

[4]. In a typical single-screw extruder used for recycling, a solid polymer feed is conveyed along a rotating screw inside a heated barrel. Band heaters clamped on the barrel supply heat, and movement is by mechanical work (shear) from the screw. The energy input from heaters and drive systems is largely used to melt and transport the polymer, after which much of that heat is lost to cooling media (air or water) in downstream equipment.

[5]. In practice, a sizable fraction of the electrical energy supplied to the extruder ends up as waste heat rejected to the environment. For example, heaters and cooling systems in conventional extruders can waste 20–30% or more of their input power through convective losses. Reducing these losses through better thermal design can therefore yield significant energy and cost savings. Prior studies emphasize that extrusion machinery is a prime candidate for efficiency improvements.

[6]. A review found that polymer extrusion is broadly representative of energy-intensive processes in plastics manufacturing and that incremental gains (e.g. better drive systems, insulation, or waste-heat recovery) can cumulate into large savings. Modern extruder designs often focus on sophisticated motor drives and automated controls, but less attention has been given to the basic issue of heat containment around the barrel. Anecdotal industry reports highlight that retrofitting existing extruders can achieve ~8–14% energy reductions

[7]. In additive manufacturing (FFF) 3D printers, researchers have applied CFD to optimize the “hot-end” heat block design, finding that improved conduction paths and insulation stabilize the temperature output.

These insights suggest similar approaches could benefit recycling extruders. To date, there has been relatively little published on the detailed thermo-economic design of extruder heating sections. This paper aims to fill that gap by systematically comparing several heating configurations of a recycling extruder using computational simulation and analysis. Defined and modelled are three configurations of the heating sections: the baseline (uninsulated) case, a fibreglass-insulated wrap case, and a silicon-carbide composite shell case. A steady-state heat-transfer simulation is performed to assess the temperature profiles and heat losses for each case. Thermal performance is then translated into annual energy consumption and cost using representative operating conditions. By quantifying both the thermal improvement and the associated cost implications, a thermo-economic perspective on extruder design is provided. The remainder of the paper is structured as follows: the Methodology section describes the modelling approach and key equations; Design and Simulation details the geometric and material parameters; Results and Discussion presents thermal and economic outcomes; and the Conclusion summarizes the findings and potential impact.

II. METHODS

The investigation of the thermal performance of the plastic reduction machine was carried out using advanced modelling and computational techniques. The process included model creation, material property assignment, boundary condition specification, and simulation using Autodesk Fusion 360 and Autodesk CFD. The following steps outline the methods employed:

License Acquisition for Autodesk Fusion 360 and Autodesk CFD:

Licenses for Autodesk Fusion 360 (educational) and Autodesk CFD (commercial) were obtained for 3D modelling and simulation, ensuring access to comprehensive design and analysis tools. These licenses supported full functionality and legal use for the project. A detailed digital model of the plastic extruder was created using Autodesk Fusion 360 CAD software, ensuring precise fit and functionality of all components. Autodesk CFD software was used to simulate heat transfer and temperature distribution, providing a detailed analysis of the plastic extruder's performance inFigures 1-12.

Simplification was later applied to exclude components with negligible thermal effects, such as bolts and pulleys.

III. SYSTEM DESIGN

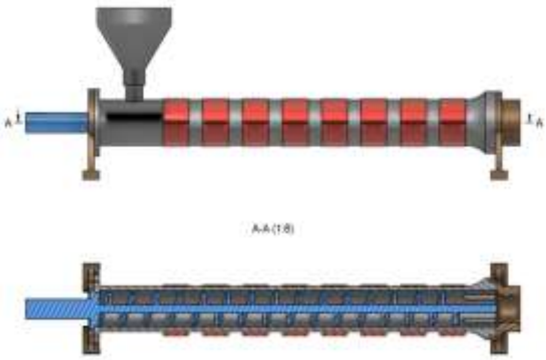

Figure 6: Plastic Reduction Machine: Front and a Sectioned Top View

Figure 7: Plastic Reduction Machine: Isometric View

Figure 8: Funnel: Isometric View

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Figure 9: Heating Bands: Isometric View

Figure 10: Shaft: Isometric View

Figure 11: Extrusion Cylinder: Isometric View

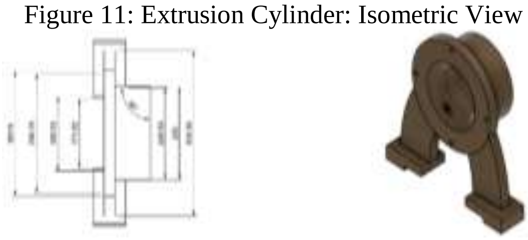

Figure 12: Front Support: Isometric View

A three-dimensional thermo-fluid model of the different extruder scenarios for simulation was designed. The baseline geometry– Figure 13, consists of a cylindrical barrel (stainless steel 304, thermal conductivity ~16 W/m·K) with ten circumferential heating bands (allocated along the barrel length) and exposed outer surfaces.

Figure 13: External Heater Bands with No Insulation

Two alternative configurations were defined: (1) Fibreglass Wrap – Figure 14, the same barrel and bands enclosed within a 10-mm-thick layer of fibreglass insulation (thermal conductivity ~0.05 W/m·K);

Figure 14: External Heater Bands with Fibreglass Insulation Wrap (Quarter-sectioned)

(2) SiC Composite Shell – Figure 15, the barrel and bands are enclosed within a rigid silicon-carbide composite housing (thickness ~5 mm, thermal conductivity ~120 W/m·K).

Figure 15: External Heater Bands with Composite Shell (Quarter-sectioned)

IV. DESIGN ANALYSIS

The geometric parameters were based on a medium-sized extruder: barrel inner diameter D = 0.10 m, effective length L = 1.2 m, and ten equally spaced heater bands each 0.12 m wide. All models included the surrounding air domain for convective losses – Figures 16-18; ambient conditions were uniform at 25°C with no forced airflow, representing natural convection. In the Baseline case - Scenario 1, these bands (modelled as stainless-steel heaters) were placed directly on the barrel with no additional covering

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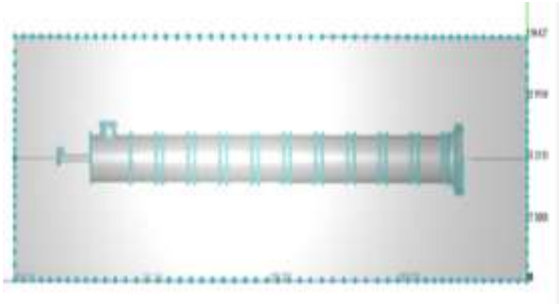

Figure 16: Scenario 1- Exposed Heater Bands within Air Volume

In Scenario 2 (Fibreglass), a 10-mm-thick fibrous insulation is wrapped fully around the barrel and bands, covering the same length.

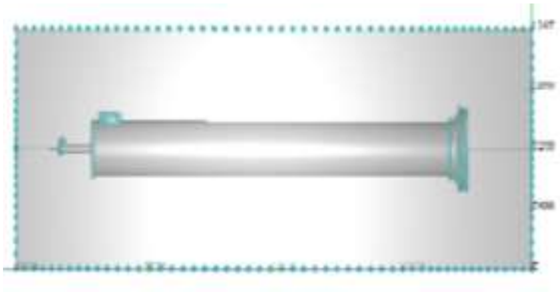

Figure 17: Scenario 2- Fibreglass Insulation Wrap within Air Volume

For Scenario 3 (SiC Shell), the bands and barrel were enclosed within a cylindrical shell of silicon-carbide composite (5 mm thick) that provided a rigid enclosure.

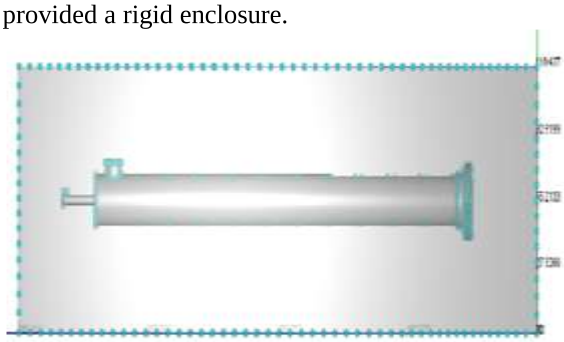

Figure 18: Scenario 3- Composite Shell Enclosure within Air Volume

Emissivity and radiation were neglected to focus on conduction-convection paths. The simulation output included temperature contours in the barrel and insulation, and the total heat flux through the outer surfaces.

NOMENCLATURE

D (m): Extruder barrel inner diameter.
L (m): Effective length of the heated barrel section.
A (m^2): Surface area of barrel-heater interface.
h ($W/m^2\cdot K$): Convective heat transfer coefficient (air to barrel).
k (W/m·K): Thermal conductivity of barrel or insulation material.
t (m): Thickness of insulation layer or shell.
U ($W/m^2\cdot K$): Overall heat transfer coefficient of barrel system.
ΔT (K or °C): Temperature difference driving heat flow.
Q (W): Heat transfer rate through barrel wall.
P (W): Input electrical power to heaters. ṁ (kg/s): Mass flow rate of molten polymer through the extruder.
c□ (J/kg·K): Specific heat of polymer.
T (°C or K): Absolute temperature.
η (–): Thermal efficiency (useful heat delivered vs. input heat).
ROI (%): Return on Investment.
CFD: Computational Fluid Dynamics.
$Q_{cylinder}$: Heat absorbed by the cylinder (J)
$Q_{transfer}$: Heat transfer by the cylinder (W)
$c_{cylinder}$: Specific heat capacity of the cylinder (J/kg·K)
$m_{cylinder}$: Mass of the cylinder (kg)
ΔT_a: Temperature rise of the cylinder (°C)
ΔT_t: Temperature difference through the cylinder (°C)
ρ: Density of the material (kg/m^3)
V_i: Voltage supplied to the heater band (V)
I: Current drawn by the heater band (A)

1. Heat Absorbed by the Extrusion Cylinder
$Q_{cylinder} = m_{cylinder} \cdot c_{cylinder} \cdot \Delta T_a$ Given:
$\rho = 8\,000\ kg/m^3$, $c_{cylinder} = 500\ J/(kg\cdot K)$
$V = 0.02\ m^3$, $\Delta T = 200\ K$
$Q_{cylinder} = 160\ kg \cdot 500\ J/(kg\cdot K) \cdot 200\ K = 16,000\ kJ$

2. Heat Transfer Through the Extrusion Cylinder:$Q_{transfer} = \frac{k\cdot A\cdot \Delta T_t}{L}$
Given:
$k = 0.1\ W/(m\cdot K)$, $A = 1.5\ m^2$
$\Delta T = 100\ K$, $L = 0.02\ m$
$Q_{transfer} = 0.1 \cdot 1.5 \cdot 100 / 0.02 = 750\ W$
3. Heat to Raise Plastic Temperature:$Q_{plastic} = m \cdot c \cdot \Delta T$
$Q_{plastic} = 0.036 \cdot 2\,300 \cdot 115 = 9,522\ W$

3. Total Heat Requirement:
$$Q_{total} = Q_{plastic} + Q_{transfer\ \ losses}$$

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= 9 522 W + 500 W = 10, 022 W

4. Electrical Power per Heater Band and Count:

P = V · I

Given: V = 230 V, I = 4.5 A

P = 230 · 4.5 = 1, 035 W

Number of Bands = $\frac{Q_{total}}{P}$

= 10 022 / 1 035 ≈ 9.68 ≈ 10 bands

V. SIMULATION SETUP

Steady-state heat-transfer simulations were performed using Autodesk CFD. The barrel and insulation materials were modelled with their temperature-dependent thermal properties. Convective heat transfer to ambient air (T_∞=25°C) was applied on all external surfaces, with a conservative uniform coefficient h ≈ 10 W/m²·K (natural convection). The screw and polymer were also modelled; however, the focus is on the temperature of the surrounding air volume, and that of the polymer within the extrusion barrels. Mesh convergence was ensured to be finer near material interfaces. The Autodesk CFD solver was run to convergence of energy residuals $<10^{-6}$. The overall heat loss from the barrel was computed by integrating convective losses over the exterior surface. To begin CFD analysis, the following materials and parameters were assigned, and configured to give more precise results, followed by the meshing of the models – Figure 19-32.

Table 1: Assigned Materials and Their Specific Heats

Name	**Assigned Materials&**	**Specific Heat** (J/kgK)
Extrusion Cylinder	Stainless Steel 304	500.00
Thermal Blanket	Fiberglass	840.00
Composite Shell	Silicon Carbide	120.00
Polymer	Polyethylene	2300.00
Surrounding Volume	Air	1005.00
Heater Bands	Stainless Steel 301	500.00

Table 2: Pre-Simulation Parameters

Parameter	**Setting**
Heat Transfer	On
Heat Generation	1,000W/Band
Base Temperature	25 °C
Solution Mode	Transient
Time Step Size	30
Stop Time	-1
Inner Iterations	5
Time Steps to Run	120
Heat Duration	60 minutes

Figure 19: Meshed Scenario 1- Exposed Heater Bands

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Figure 20: Meshed Scenario 2Fibreglass Insulation Wrap

Figure 21: Meshed Scenario 3- Composite Shell Enclosure

VI. RESULTS AND DISCUSSION

The performance of the plastic reduction machine was evaluated under the three scenarios, each representing a different insulation configuration.

Scenario 1: Baseline Configuration- No Wrap

In this configuration, the heating bands were applied externally on the extrusion cylinder without any insulation. The results revealed significant heat loss to the surrounding air volume, with temperature gradients indicating inefficient thermal retention. This scenario served as the benchmark for evaluating the effectiveness of subsequent insulation strategies and was applied for all three material cases.

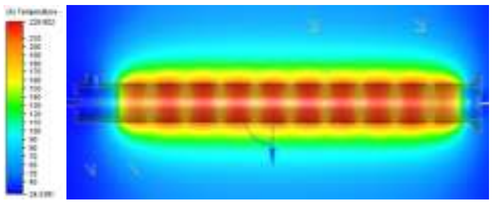

Figure 22 - Extruder With Exposed Heater Bands

Scenario 2: Fibreglass Insulation Wrap

The introduction of fibreglass insulation wraps around the heating bands led to a noticeable improvement in thermal performance. The temperature distribution indicated a slightly more uniform heat retention across the extrusion cylinder and scenarios, reducing heat loss compared to the baseline scenario.

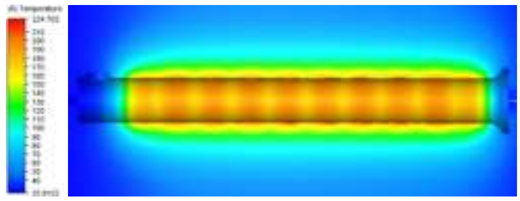

Figure 23 - Extruder with Fibreglass insulation wrap

Scenario 3: Composite Shell Enclosure

Encasing the heating bands and extrusion cylinder within a composite silicon carbide shell still enhanced thermal retention when compared to the baseline scenario. The high thermal conductivity of the silicon carbide shell however still contributed to a high heat flux to the environment, evidenced by the heat flux escaping the system.

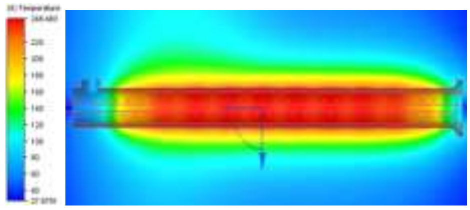

Figure 24 - Extruder With Composite Shell Enclosure

TEMPERATURE DISTRIBUTION ANALYSIS

The temperature distribution plots for each scenario demonstrated the impact of insulation configurations on thermal performance. In Scenario 1, significant temperature gradients were observed, indicating heat loss to the environment. Scenarios 2 and 3 showed progressively better temperature retention, with Scenario 2 having the best heat case

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across the extrusion cylinder. The average air and rise in polyethylene temperatures for each period are plotted in the graphs below:

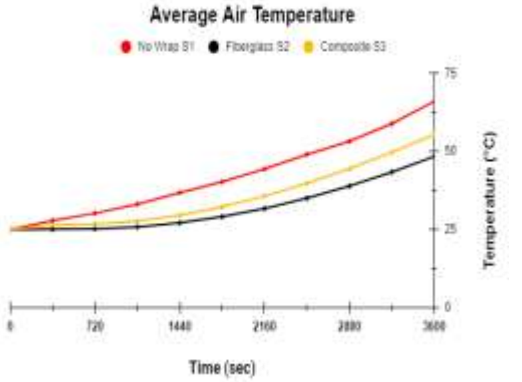

Figure 25: Temperature Rise in the Surrounding Air

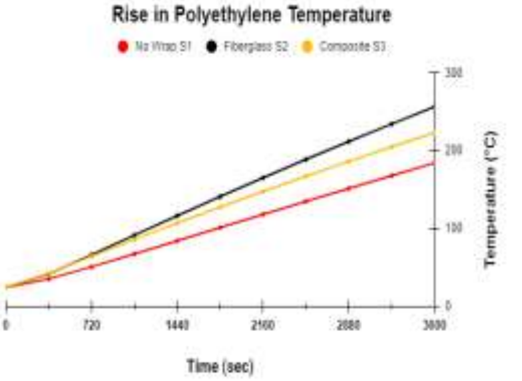

Figure 26: Temperature Rise in Polyethylene

THERMAL EFFICIENCY

The simulation conducted on a 54.28kg, 50mm thick polyethylene block for 3600 seconds using a Total Heat Generation of 10,000 W (1,000 W per heater band) yielded the following insights:

Table 3: Efficiency gain on reaching 135 °C

Scenario	t135 °C (s)	Energy Spent (KWh)	Efficiency (%)
No wrap	2430	6.75	—
Fiberglass	1710	4.75	42.1%
Composite Shell	1890	5.25	28.6%

ECONOMIC ANALYSIS

Based on the thermal analysis (Table 4.2.6), the times to heat to 135 °C are 2430 s (No Wrap), 1710 s (Fibreglass), and 1890 s (Composite). Assuming a constant 10 kW heater (as used in the analysis), and using an industrial tariff of \$0.06 per kWh, ≈₦96/kWh at current rates (United4Efficiency, 2022) and an exchange rate of about ₦1606.5 per US\$ (XE, 2025), we calculate the cost for each scenario per cycle, per month (30 cycles), and per year (360 cycles):

Table 4: Cost Savings with each scenario

Scenario	Annual Cost (NGN)	Savings vs. No Wrap (NGN)
No Wrap	₦234,231	—
Fiberglass	₦164,829	₦69,402
Composite Shell	₦182,179	₦52,051

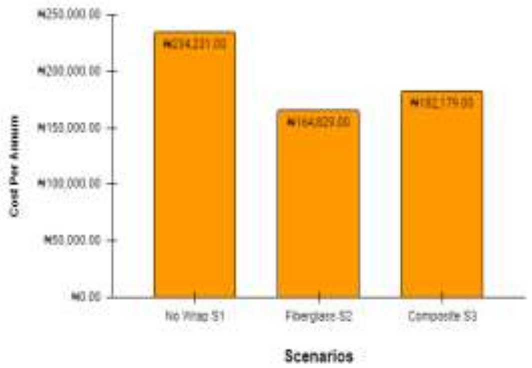

Figure 27: Comparative Operational Cost Per Annum

For clarification, a theoretical heat-balance check was applied: assuming an overall heat transfer rate $Q = U \cdot A \cdot \Delta T$ [9], where U the effective heat-transfer coefficient and A the heated barrel area, the simulation results matched within a few percents. Here, U accounts for both metal conduction and external convection (for a single-layer cylinder) $\frac{1}{U} = \frac{1}{h} + \frac{t}{k} + \frac{1}{h}$. For the economic analysis, the simulation results (heat loss or required heater power) were used to estimate annual electricity use. The power to maintain the setpoint is $P \approx Q$ (since the drive contribution was assumed constant across cases). Annual energy consumption is $E = P \times H_{op}$ where H_{op} is annual operating hours (e.g. 4,000 h/year). At a unit electricity cost c_e (e.g. \$0.10/ kWh), the annual heating cost is $C = E \times c_e$. The incremental annual savings of each design over the baseline are $\Delta C = (P_{base} - P_{config}) \cdot H_{op} \cdot c_e$. A simple payback was evaluated by comparing the extra capital cost of adding insulation versus the annual savings. All cost calculations neglect factors like maintenance or downtime and assume continuous, stable operation.

For economic sizing, the payback period (years) was computed as

$$\text{Payback} = \frac{\Delta C_{capital}}{\Delta C_{annual}}$$

Where $\Delta C_{capital}$ is the additional upfront cost of insulation and ΔC_{annual} is the first-year energy saving? All economic figures assume continuous operation and neglect maintenance or downtime.

VII. CONCLUSION

This thermo-economic analysis highlights the challenge and importance of efficient thermal design in plastic recycling extruders. Conventional extruders suffer significant heat losses during melting, which drives up energy use and carbon emissions. In our study, adding external insulation around the heater bands substantially increased the fraction of heat retained in the polymer, on the order of tens of percents, while certain enclosures (like a high-conductivity shell) offered little benefit. These results emphasize that **insulation works**: simple materials like fibreglass blankets can make a large difference in energy efficiency.

The comparisons clarify the path forward. Insulation emerges as a **high-impact, low-cost** improvement for existing extruders. For new machine designs, combining optimal insulation with other advances (such as waste-heat recovery or smarter control systems) could yield even greater savings. In the broader context of sustainability, improving extruder heating efficiency contributes directly to reducing the environmental footprint of plastic recycling. As circular economy goals push for higher recycling rates and lower waste, studies like this underscore how engineering design can help meet those objectives. Ultimately, continued research and development of efficient thermal systems will be essential to making large-scale plastics recycling truly viable and eco-friendly.

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