An Analytical and Experimental Heat Transfer Investigation of a mother-Baby Plastic Granule Extruder Machine with Heat Recovery Integration

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Abstract-This study presents an analytical and experimental heat transfer investigation of a mother-baby plastic granules extruder machine with the integration of a heat recovery structure. The analytical model was developed by considering conduction through the heater to the barrel surface, conduction across the barrel wall, convection between the barrel inner surface and the raw plastic, and additional heat generation due to shear and friction of the rotating screw. To validate the model, experimental trials were conducted on an LDPE processing extruder unit under two cases: (i) without heat recovery integration and (ii) with a CRC sheet-based heat recovery structure installed between the mother and baby units. A total of 48 temperature readings (8 readings per day for 3 consecutive days, in both cases) were collected to analyse the thermal response. The results showed close agreement between analytical predictions and experimental observations, with notable variations in temperature distribution across the barrel and plastic melt zones. The incorporation of the heat recovery structure demonstrated improved utilization of the rejected thermal energy, thereby confirming the effectiveness of the proposed design. This combined analytical–experimental approach provides a detailed understanding of the heat transfer processes in extrusion machines and highlights potential pathways for enhancing thermal performance and energy efficiency in plastic recycling operations.

Index Terms-Plastic recycling, Mother-baby extruder, Heat transfer analysis, Heat recovery integration, Thermal performance, Energy efficiency, LDPE extrusion, Analytical modelling.

NOMENCLATURE	*GREEK SYMBOLS*
Q – Heat transfer, W (Watt)	k – Thermal conductivity, W/m•k
$Q_{cond, outer}$ – Conduction heat transfer through barrel outer wall, W (Watt)	h – Convective heat transfer coefficient, W/m^2•k
$Q_{cond, inner}$ – Conduction heat transfer through barrel inner wall, W (Watt)	A – Surface area involved in heat transfer, m^2
$Q_{conv, inner}$ – Convection heat transfer through barrel inner wall, W (Watt)	L – Barrel length, m
$Q_{friction}$ - Heat generation due to friction, W (Watt)	d – Barrel diameter, m
Q_{useful} – Useful heat utilized by raw material, W (Watt)	P – Power input to motors, HP
Q_{total} – Total heat input, W (Watt)	
η_{th} – Thermal efficiency, %	
C_p – Specific heat capacity, kJ/kgK	
T_{inlet} – Inlet temperature, °C	
T_{outlet} – Outlet temperature, °C	
T_{heater} – Heater surface temperature, °C	

I. INTRODUCTION

Plastic extrusion is a widely used manufacturing and recycling process for converting waste polymers into reusable granules. Among different plastics, low-density polyethylene (LDPE) is commonly recycled due to its widespread use in packaging and consumer products [1]. The efficiency of extrusion depends heavily on the heat transfer between the electrical heaters, the barrel, and the plastic material. Inadequate thermal management often results in higher specific energy consumption (SEC), poor product quality, and increased operational costs [2,3].

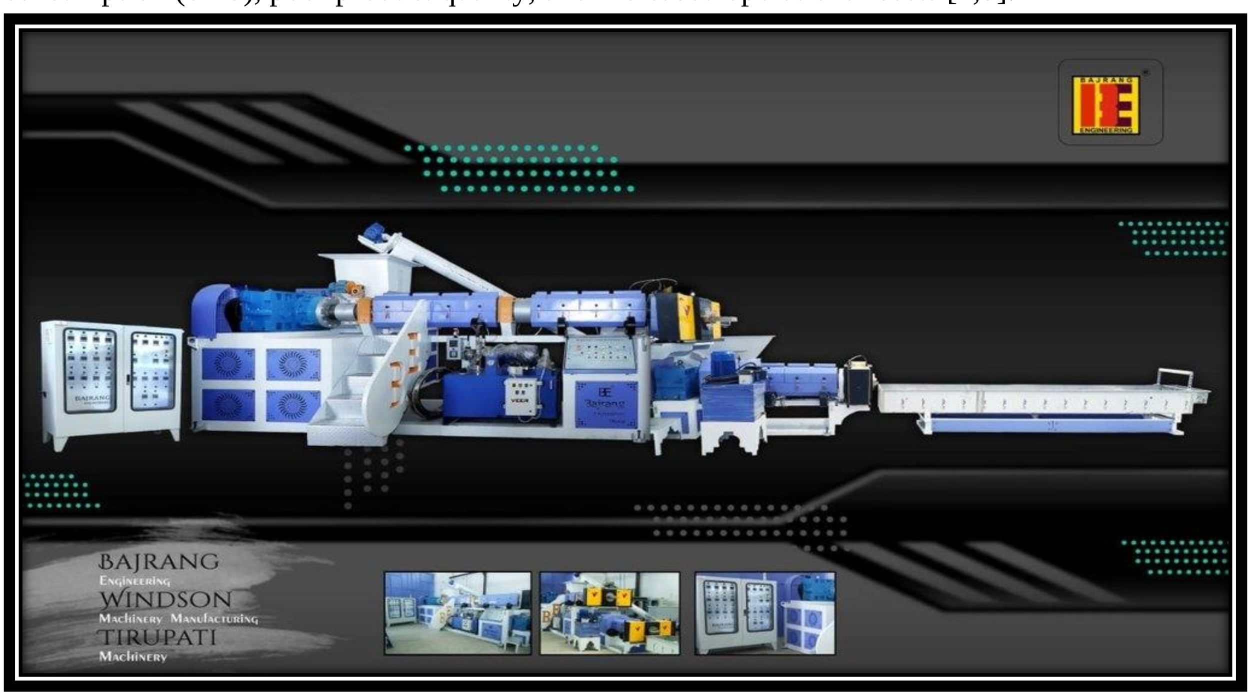

Figure 1: Broad View of The Industrial Mother-Baby Plastic Granule Extruder Machine

In extrusion systems, heating is primarily achieved through electrical heaters mounted on the barrel surface. The supplied heat undergoes multiple transfer mechanisms: conduction through the barrel wall, convection to the rotating screw and molten polymer, and internal heat generation due to shear friction [4]. The accurate estimation of these heat transfer modes is essential for improving energy efficiency and thermal performance. Several studies have analysed conduction and convection heat transfer in extrusion systems [5,6], while others have emphasized the impact of screw rotation and polymer rheology on thermal distribution [7]. However, limited research exists on integrating heat recovery mechanisms into extruder systems to reduce energy losses [8,9].
The present work aims to address this gap by performing a detailed analytical and experimental heat transfer investigation of a mother-baby extruder machine used for LDPE recycling. The study integrates three consecutive days of experimental trials, with eight readings per day, under two conditions: (i) without heat recovery structure, and (ii) with a CRC sheet-based structure positioned between the mother and baby units. The results were compared with analytical heat transfer models.

The novelty of this research lies in combining theoretical heat transfer modelling with real-time experimental validation on an industrial scale extrusion system. This dual approach not only improves the understanding of heater-barrel-polymer thermal interactions but also provides practical insights for designing more energy efficient recycling extruders.

II. METHODOLOGY

The present study employs a combined analytical modelling and experimental measurement approach to investigate the heat transfer performance of a mother–baby plastic granules extruder. The methodology is divided into two major parts:
(i) analytical heat transfer model formulation
(ii) experimental procedure for data collection with and without heat recovery integration.

II.I ANALYTICAL HEAT TRANSFER MODEL

The thermal behaviour of the mother–baby plastic granules extruder was analysed by developing an analytical model based on classical heat transfer principles. The model considered the following mechanisms:

II.I.I. CONDUCTION THROUGH BARREL WALL:

Heat conduction occurs radially across the extruder barrel from the outer heated surface to the inner wall in contact with the polymer. This was modelled using cylindrical conduction relations

$$Q = \frac{2\pi kL\,(T_{heater} - T_{barrel\ outer})}{\ln(\frac{r_{outer}}{r_{inner}})} \qquad (1)$$

Were,

- Q is the heat transfer (W),
- k is the thermal conductivity of the barrel material (W/m·K),
- L is the length of the barrel (m),

- router is the outer radius of the barrel (m),
- r_{inner} is the outer radius of the barrel (m),
- T_{heater} is the heater temperature (˚C),
- T_{barrel} outer is the barrel outer temperature (˚C).

II.I.II CONDUCTION FROM BARREL INNER SURFACE TO SOLID RAW MATERIAL:

At the polymer–barrel interface, a conduction mechanism dominates as solid granules initially absorb heat from the inner barrel wall:

$$Q = \frac{kpA(T_{\text{barrel inner}} - T_{\text{raw material}})}{x} \quad (2)$$

Were,

- k_p is the thermal conductivity of polymer,
- A is the surface area
- x is barrel thickness.

II.I.III. CONVECTION FROM BARREL INNER WALL TO RAW MATERIAL:

The inner wall transfers heat to the solid polymer granules and partially molten resin by convection. Newton's law of cooling was applied:

$$Q = hA\,(T_{\text{barrel inner}} - T_{\text{raw material}}) \quad (3)$$

Were,

- h is the convective heat transfer coefficient ($W/m^2{\cdot}K$).

II.I.IV ADDITIONAL HEAT GENERATION DUE TO SHEAR AND FRICTION:

As the screw rotates, viscous dissipation and frictional effects generate additional heat within the polymer melt. This contribution was estimated from the screw speed, torque, and polymer rheology characteristics.

$$Q = \eta \times P \quad (4)$$

Were,

- η is the mechanical efficiency (assumed ~ 60%),
- P is the motor power rating (in HP), converted to kW.

II.I.V OVERALL USEFUL HEAT TRANSFER:

The total useful heat transferred to the polymer was expressed as:

$$Q_{useful} = Q_{cond\ polymer} + Q_{conv} \quad (5)$$

II.I. VI TOTAL HEAT SUPPLIED:

The total heat supplied was expressed as:

$$Q_{total\ heat} = Q_{cond\ inner} + Q_{shear} \quad (6)$$

II.II EXPERIMENTAL SETUP

To validate the analytical model, experiments were conducted on a mother–baby plastic granules extruder machine processing LDPE waste. The specifications of both units are summarized in Table 1.

Figure 2: Complete view of Mother-Baby plastic granule extruder machine (industrial setup)

Table 1: Specifications of mother and baby extruder units

Sr. No.	Parameter	Value		Unit
		Mother Unit	*Baby Unit*	
1	Barrel inside diameter	150	135	mm
2	Barrel outside diameter	240	215	mm
3	Barrel length	14	5	ft
4	Inlet temperature	53	129	°C
5	Outlet temperature	140	144	°C
6	Barrel outer temperature	146	151	°C
7	Barrel inner temperature	130	143	°C
8	Running load	75	25	HP

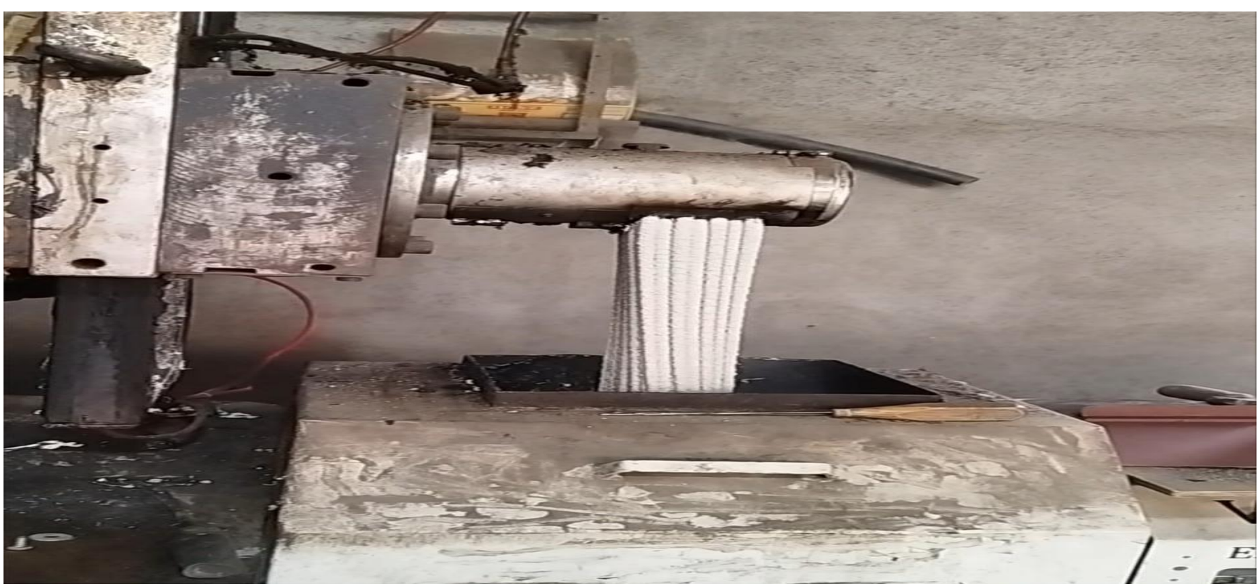
Figure 3: Open Space between Mother-Baby Unit before heat recovery structure integration

II.III HEAT RECOVERY STRUCTURE

A specially designed heat recovery structure was integrated in the open space between the mother and baby unit to minimize temperature loss. The structure utilized a CRC sheet assembly to retain and redirect thermal energy from the outgoing polymer stream of the mother unit into the inlet of the baby unit. The design and integration of this structure were reported in our previous experimental work [14], and its performance is evaluated in this study in conjunction with the analytical model.

Figure 4: Designed heat recovery structure using CRC sheet with red oxide coating

Figure 5: Assembled view of mother unit, heat recovery structure and baby unit (integrated setup)

Thermocouples were placed at strategic locations including: heater surface, barrel outer surface, barrel inner surface, polymer inlet and outlet of both mother and baby units.

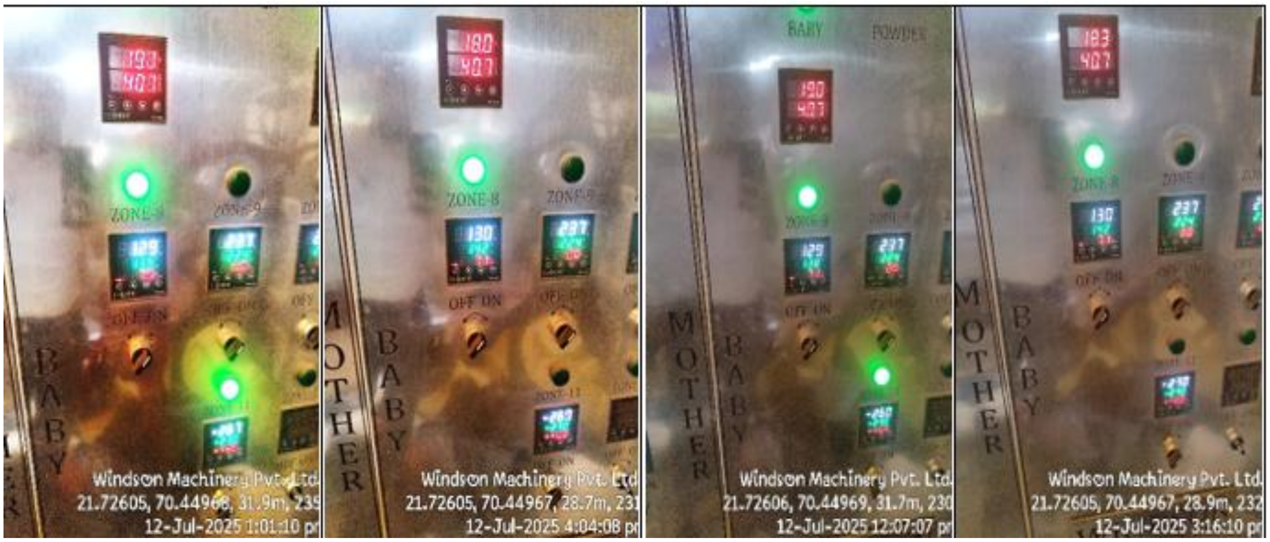

Figure 6: Schematic diagram of temperature sensor placement (random readings)

III. EXPERIMENTAL DATA PRESENTATION

To validate the analytical model, experimental investigations were carried out on the mother–baby plastic granules extruder system under two operating scenarios:

1) Without heat recovery structure
2) With heat recovery structure (CRC sheet arrangement between mother and baby units).

III.I Data Collection:

Experiments were conducted for three consecutive days and on each day, eight sets of readings were recorded at equal time intervals. Thus, a total of 48 readings were collected for both cases (with and without heat recovery). The key measured parameters were:

1) Time of recording (min)
2) Inlet temperature of baby extruder (°C)
3) Outlet temperature of baby extruder (°C)
4) Recovered temperature due to CRC sheet structure (°C)

Day – 1,

Table 2: Baby unit inlet temperatures before and after heat recovery integration (Day 1)

Time	Mother Unit Outlet Temp (°C)	Baby Unit Inlet Temp Before Cover (°C)	Baby Unit Inlet Temp After Cover (°C)	Temperature Recovered (°C)
10:00	139	128	138	10
11:00	140	129	139	10
12:00	140	128	139	11
01:00	140	129	140	11
02:00	140	129	140	11
03:00	139	130	139	9

04:00	139	129	138	9
05:00	139	128	137	9

Day – 2,

Table 3: Baby unit inlet temperatures before and after heat recovery integration (Day 2)

Time	Mother Unit Outlet Temp (°C)	Baby Unit Inlet Temp Before Cover (°C)	Baby Unit Inlet Temp After Cover (°C)	Temperature Recovered (°C)
10:00	140	127	138	11
11:00	140	129	139	10
12:00	140	129	139	10
01:00	140	130	140	10
02:00	140	132	141	9
03:00	139	130	139	9
04:00	139	130	139	9
05:00	139	129	138	9

Day – 3,

Table 4: Baby unit inlet temperatures before and after heat recovery integration (Day 3)

Time	Mother Unit Outlet Temp (°C)	Baby Unit Inlet Temp Before Cover (°C)	Baby Unit Inlet Temp After Cover (°C)	Temperature Recovered (°C)
10:00	140	128	137	9
11:00	140	128	138	10
12:00	140	130	138	8
01:00	140	131	139	8
02:00	140	131	141	10
03:00	140	132	142	10
04:00	139	132	142	10
05:00	139	131	141	10

Table 5: Average experimental values for before and after heat recovery integration

Sr. No.	Parameter	Before heat recovery integration				After heat recovery integration				Improvement
1	Baby Unit Inlet Temperature (˚C)	128.75	129.50	130.38	129.54	138.75	139.12	139.75	139.20	Temperature increased (09.66 ˚C)
2	Baby Unit Outlet Temperature (˚C)	144.00	144.00	144.00	144.00	144.00	144.00	144.00	144.00	Same as maintain-ned
3	ΔT Across Baby Unit (˚C)				14.46				4.85	Reduced load on heater

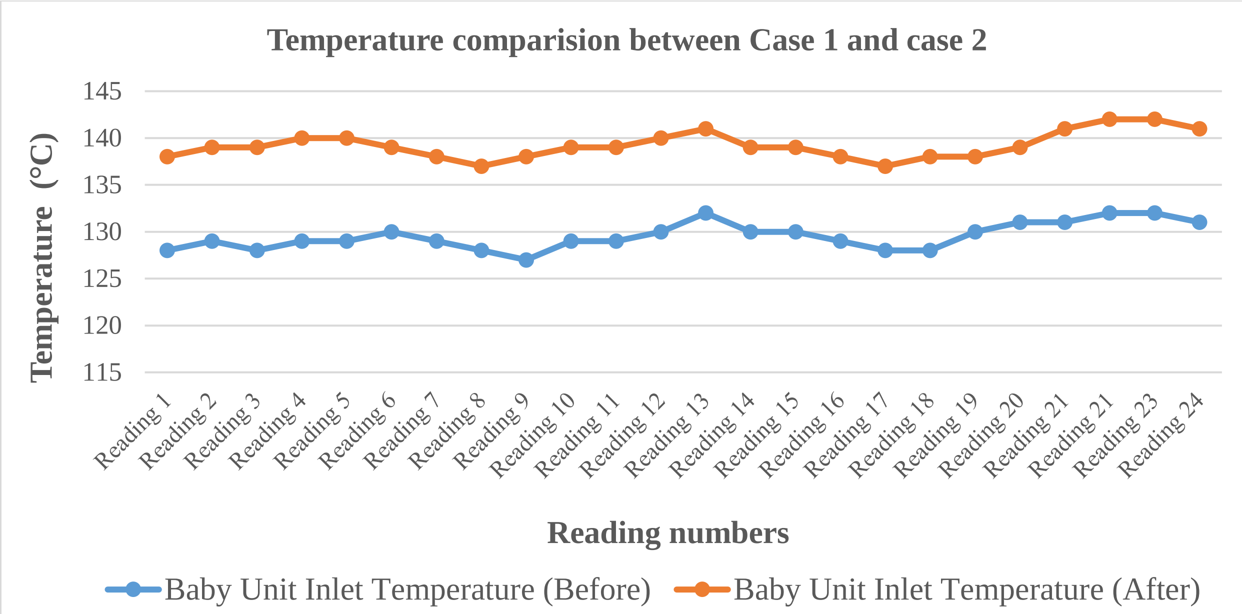

Figure 7: Time wise comparison of baby unit inlet temperature before structure and after structure

Figure 7 shows the inlet temperature comparison of the baby unit before and after integration of the heat recovery structure. A noticeable increase in inlet temperature was observed post structure, indicating successful recovery of thermal energy that would otherwise be lost. This contributed to improved thermal performance and reduced energy consumption in the baby unit.

IV. CALCULATIONS

IV.I Mother unit:

IV.I.I Heat transfer through conduction from barrel outer surface to barrel inner surface:

$$Q = \frac{2\pi kL\,(T_{heater} - T_{barrel\ outer})}{\ln(\frac{r_{outer}}{r_{inner}})} = 35.89\ kW$$

IV.I.II Heat transfer through conduction from barrel inner surface to raw material:

$$Q = \frac{kpA(T_{barrel\ inner} - T_{raw\ material})}{x} = 37.94\ kW$$

IV.I.III Heat transfer through convection from barrel inner surface to raw material:

$$Q = hA\ (T_{barrel\ inner} - T_{raw\ material}) = 10.19\ kW$$

IV.I.IV Additional heat generation due to friction:

$$Q = \eta \times P = 33.57\ kW$$

IV.II Baby unit (before heat recovery integration):

IV.II.I Heat transfer through conduction from barrel outer surface to barrel inner surface:

$$Q = \frac{2\pi kL\,(T_{heater} - T_{barrel\ outer})}{\ln(\frac{r_{outer}}{r_{inner}})} = 6.38\ kW$$

IV.II.II Heat transfer through conduction from barrel inner surface to raw material:

Table 6: Heat transfer values through conduction from barrel inner surface to raw material for day-1

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 1	10:00 AM	2.63	2.50
2		11:00 AM	2.46	
3		12:00 PM	2.63	
4		1:00 PM	2.46	
5		2:00 PM	2.46	
6		3:00 PM	2.28	
7		4:00 PM	2.46	
8		5:00 PM	2.63	

Table 7: Heat transfer values through conduction from barrel inner surface to raw material for day-2

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 2	10:00 AM	2.80	2.37
2		11:00 AM	2.46	
3		12:00 PM	2.46	
4		1:00 PM	2.28	
5		2:00 PM	1.93	
6		3:00 PM	2.28	
7		4:00 PM	2.28	
8		5:00 PM	2.46	

Table 8: Heat transfer values through conduction from barrel inner surface to raw material for day-3

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 3	10:00 AM	2.80	2.22
2		11:00 AM	2.46	
3		12:00 PM	2.46	
4		1:00 PM	2.28	
5		2:00 PM	1.93	
6		3:00 PM	2.28	
7		4:00 PM	2.28	
8		5:00 PM	2.46	

IV.II.III Heat transfer through convection from barrel inner surface to raw material:

Table 9: Heat transfer values through convection from barrel inner surface to raw material for day-1

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 1	10:00 AM	0.85	0.81
2		11:00 AM	0.80	
3		12:00 PM	0.85	
4		1:00 PM	0.80	
5		2:00 PM	0.80	
6		3:00 PM	0.74	
7		4:00 PM	0.80	
8		5:00 PM	0.85	

Table 10: Heat transfer values through convection from barrel inner surface to raw material for day-2

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 2	10:00 AM	0.90	0.77
2		11:00 AM	0.80	
3		12:00 PM	0.80	
4		1:00 PM	0.74	
5		2:00 PM	0.63	
6		3:00 PM	0.74	
7		4:00 PM	0.74	
8		5:00 PM	0.80	

Table 11: Heat transfer values through convection from barrel inner surface to raw material for day-3

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 3	10:00 AM	0.85	0.72
2		11:00 AM	0.85	
3		12:00 PM	0.74	
4		1:00 PM	0.69	
5		2:00 PM	0.69	
6		3:00 PM	0.63	
7		4:00 PM	0.63	
8		5:00 PM	0.69	

IV.II.IV Additional heat generation due to friction:

$$Q = \eta \times P = 11.19 \text{ kW}$$

IV.III Baby unit (after heat recovery integration):

IV.III.I Heat transfer through conduction from barrel outer surface to barrel inner surface:

$$Q = \frac{2\pi kL\,(T_{heater} - T_{barrel\ outer})}{\ln(\frac{r_{outer}}{r_{inner}})} = 6.38\ kW$$

IV.III.II Heat transfer through conduction from barrel inner surface to raw material:

Table 10: Heat transfer values through conduction from barrel inner surface to raw material for day-1

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 1	10:00 AM	0.89	0.75
2		11:00 AM	0.71	
3		12:00 PM	0.71	
4		1:00 PM	0.53	
5		2:00 PM	0.53	
6		3:00 PM	0.71	
7		4:00 PM	0.89	
8		5:00 PM	1.06	

Table 11: Heat transfer values through conduction from barrel inner surface to raw material for day-2

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 2	10:00 AM	0.89	0.69
2		11:00 AM	0.71	
3		12:00 PM	0.71	
4		1:00 PM	0.53	
5		2:00 PM	0.36	
6		3:00 PM	0.71	
7		4:00 PM	0.71	
8		5:00 PM	0.89	

Table 12: Heat transfer values through conduction from barrel inner surface to raw material for day-3

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 3	10:00 AM	1.06	0.58
2		11:00 AM	0.89	
3		12:00 PM	0.89	
4		1:00 PM	0.71	
5		2:00 PM	0.36	
6		3:00 PM	0.18	
7		4:00 PM	0.18	
8		5:00 PM	0.36	

IV.III.III Heat transfer through convection from barrel inner surface to raw material:

Table 13: Heat transfer values through convection from barrel inner surface to raw material for day-1

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 1	10:00 AM	0.29	0.25
2		11:00 AM	0.23	
3		12:00 PM	0.23	
4		1:00 PM	0.18	
5		2:00 PM	0.18	
6		3:00 PM	0.23	
7		4:00 PM	0.29	
8		5:00 PM	0.35	

Table 14: Heat transfer values through convection from barrel inner surface to raw material for day-2

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 2	10:00 AM	0.29	0.23
2		11:00 AM	0.23	
3		12:00 PM	0.23	
4		1:00 PM	0.18	
5		2:00 PM	0.12	
6		3:00 PM	0.23	
7		4:00 PM	0.23	
8		5:00 PM	0.29	

Table 15: Heat transfer values through convection from barrel inner surface to raw material for day-3

Sr. No.	Day	Time	Heat Transfer (kW)	Average (kW)
1	Day 3	10:00 AM	0.35	0.19
2		11:00 AM	0.29	
3		12:00 PM	0.29	
4		1:00 PM	0.23	
5		2:00 PM	0.12	
6		3:00 PM	0.06	
7		4:00 PM	0.06	
8		5:00 PM	0.12	

IV.III.IV Additional heat generation due to friction:

$$Q = \eta \times P = 11.19 \text{ kW}$$

IV.IV Heater load:

Table 16: Values of Q with baby unit inlet temperature before and after heat recovery integration for the day-1 (value of m is taken as an 80 kg/hr. as per extruder capacity)

Day	Time	Baby Inlet Temperature Before Structure	Baby Inlet Temperature After Structure	ΔT (Before)	ΔT (After)	Q in kWh/hr (Before)	Q in kWh/hr (After)
Day 1	10:00	128	138	16	6	0.746	0.280
	11:00	129	139	15	5	0.700	0.233
	12:00	128	139	16	5	0.746	0.233
	01:00	129	140	15	4	0.700	0.187
	02:00	129	140	15	4	0.700	0.187
	03:00	130	139	14	5	0.653	0.233
	04:00	129	138	15	6	0.700	0.280
	05:00	128	137	16	7	0.746	0.326

Table 17: Values of Q with baby unit inlet temperature before and after heat recovery integration for the day-2 (value of m is taken as an 80 kg/hr. as per extruder capacity)

Day	Time	Baby Inlet Temperature Before Structure	Baby Inlet Temperature After Structure	ΔT (Before)	ΔT (After)	Q in kWh/hr (Before)	Q in kWh/hr (After)
Day 2	10:00	127	138	17	6	0.793	0.280
	11:00	129	139	15	5	0.700	0.233
	12:00	129	139	15	5	0.700	0.233
	01:00	130	140	14	4	0.653	0.187
	02:00	132	141	12	3	0.560	0.140
	03:00	130	139	14	5	0.653	0.233
	04:00	130	139	14	5	0.653	0.233
	05:00	129	138	15	6	0.700	0.280

Table 18: Values of Q with baby unit inlet temperature before and after heat recovery integration for the day-3 (value of m is taken as an 80 kg/hr. as per extruder capacity)

Day	Time	Baby Inlet Temperature Before Structure	Baby Inlet Temperature After Structure	ΔT (Before)	ΔT (After)	Q in kWh/hr (Before)	Q in kWh/hr (After)
Day 3	10:00	128	137	16	7	0.746	0.326
	11:00	128	138	16	6	0.746	0.280
	12:00	130	138	14	6	0.653	0.280

	01:00	131	139	13	5	0.606	0.233
	02:00	131	141	13	3	0.606	0.140
	03:00	132	142	12	2	0.560	0.093
	04:00	132	142	12	2	0.560	0.093
	05:00	131	141	13	3	0.606	0.140

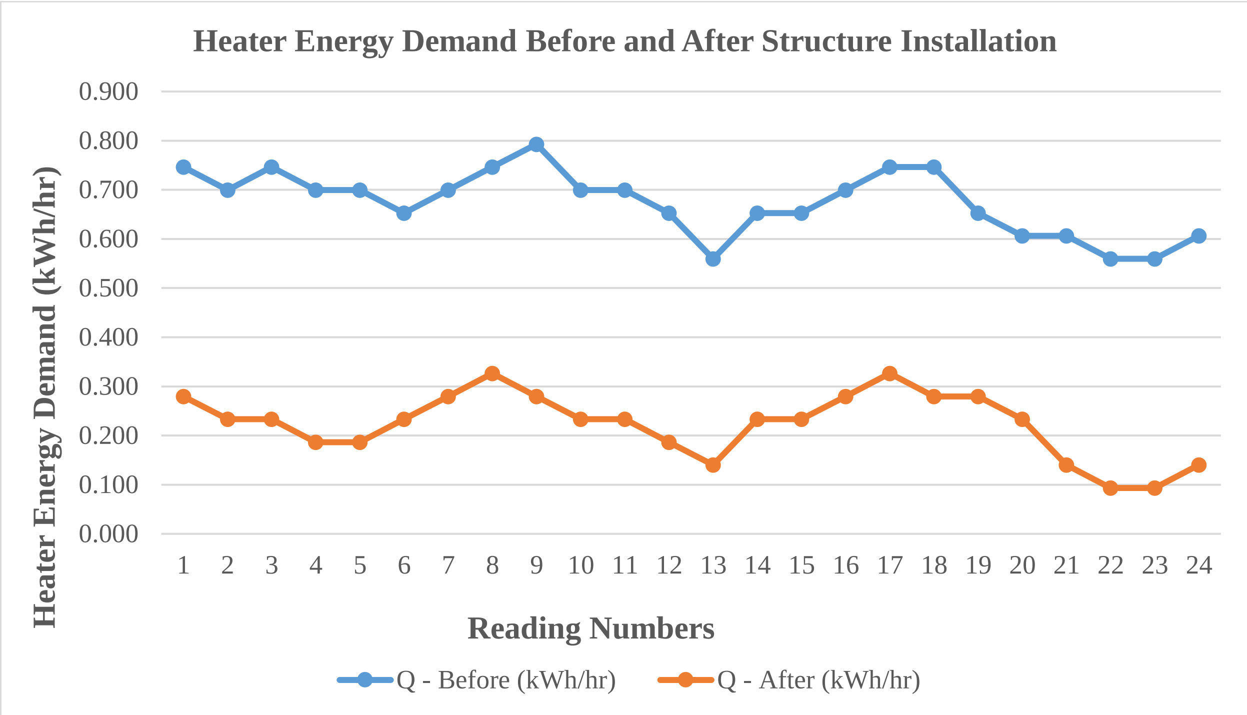

Figure 8: Heater energy demand comparison of baby unit inlet temperature before and after heat recovery integration

Figure 8 shows that after the integration of the heat recovery structure between the mother and baby extruder units, a clear reduction in heat energy demand was observed. The recovered heat from the mother unit effectively preheated the polymer entering the baby unit, thereby reducing the additional heating requirement. The experimental data recorded over three days (eight readings per day) clearly demonstrated a consistent decrease in heater energy input after integration. The plotted chart illustrates that the inlet temperature of the baby unit increased due to heat recovery, which in turn lowered the net heat supplied by its heaters. This outcome confirms that the heat recovery system successfully minimized external thermal energy demand, improving the overall sustainability and energy efficiency of the extrusion process.

V. RESULTS AND DISCUSSION

The experimental outcomes clearly confirmed the impact of the heat recovery integration between the mother and baby extruder units. In the starting point case (without heat recovery integration), the baby extruder inlet temperature was observed to be approximately 129.54 °C, requiring significant heater energy input to reach the desired processing temperature of 139.75 °C. After introducing the heat recovery structure, the inlet temperature increased to 10.21 °C, thereby reducing the heater energy demand. Quantitatively, the total heater energy consumption decreased from 0.674 kWh/hr. to 0.223 kWh/hr. which corresponds to a reduction of approximately 33.08 %. This improvement can be recognised to the recovery of waste heat from the mother unit barrel, which otherwise dissipated into the surrounding environment. By transferring this recovered heat directly to the baby unit, the system utilized the available energy more efficiently, thereby lowering on external heating. The results not only validate the effectiveness of the heat recovery integration but also indicate a possible pathway for improving thermal management in extrusion systems.

VI. CONCLUSION

This study offered an analytical and experimental investigation of heat transfer phenomena in a mother–baby plastic granule extruder system with heat recovery integration. By introducing a simple heat recovery structure between these two units, an important portion of waste heat from the mother extruder was effectively utilized to preheat the feed zone of the baby extruder. As a result, the inlet temperature of the baby unit increased, leading to a prominent reduction in heater energy demand. The results confirm that heat recovery integration improves overall energy utilization and contributes to more supportable extrusion processing without negotiating product quality. The approach proves the possible of adopting reflexive heat recovery solutions in industrial extrusion systems to reduce operational costs and improve energy efficiency.

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REFERENCES

[1] Kumar, R., Gupta, R., & Sharma, M. - Energy optimization in polymer extrusion systems using heat recovery and predictive control. Energy Reports, 9 (2023) 115–128.
[2] Zhang, L., & Liu, Y. - Experimental study on energy recovery and efficiency enhancement in plastic extrusion. Journal of Cleaner Production, 338 (2022) 130553.
[3] Singh, A., & Tiwari, V. - Thermal analysis of plastic recycling extruder with energy recovery system. Journal of Thermal Engineering, 7(5) (2021) 841–850.

[4] Deshmukh, V., & Suresh, K. - Numerical study of heat transfer in polymer extrusion barrel and screw geometry optimization. International Journal of Heat and Mass Transfer, 153 (2020) 119635.

[5] Jagtap, M. S., & Patil, N. G. - Energy consumption and heat recovery analysis of LDPE extrusion. International Journal of Energy Research, 44(12) (2020) 9564–9574.

[6] Hassan, M. A., & Abou-Elfadl, T. - Enhancing energy efficiency of twin-screw extruders with heat recovery mechanisms. Renewable Energy, 132 (2019) 761–771.

[7] Ghose, A., & Das, R. - Evaluation of energy conservation methods in extrusion of recycled plastics. Journal of Materials Processing Technology, 266 (2019) 12–22.

[8] Kalyani, M., & Satish, G. - Thermodynamic modeling of LDPE in extruder barrel for thermal performance improvement. Applied Thermal Engineering, 137 (2018) 582–590.

[9] Park, S., & Lee, D. H. - A comparative study of thermal energy losses in single and twin-screw extrusion systems. Energy, 149 (2018) 187–195.

[10] Ko, S. H., & Lin, J. H. - Experimental investigation of thermal behavior in plastic extrusion with recycled polymer. Polymer-Plastics Technology and Engineering, 56(4) (2017) 350–360.

[11] Ananth, P., & Kumar, R. - Analytical study on specific energy consumption in polymer processing machines. International Journal of Sustainable Engineering, 10(2) (2017) 103–111.

[12] Liao, Y., & Shen, H. - Energy analysis of plastic extrusion systems using exergy and pinch technology. Energy Conversion and Management, 122 (2016) 115–124.

[13] Hossain, M. T., & Rashid, M. - Numerical modeling and validation of heat transfer in extruder barrel for LDPE. Journal of Manufacturing Processes, 20 (2015) 507–515.

[14] Jain, N., & Mehta, R. - Experimental evaluation of thermal characteristics in polymer extrusion. Journal of Polymer Engineering, 34(7) (2014) 659–666.

[15] Sutar, P. P., & Joshi, D. S. - Specific energy consumption analysis of plastic granules extrusion using heat integration. Energy Procedia, 14 (2012) 896–902.

[16] Smith, T., & Zhang, W. - Investigation of recycled LDPE processing in twin screw extruder. Journal of Applied Polymer Science, 121(2) (2011) 456–462.

[17] Kamal, M. R., & Isayev, A. I. - Thermo mechanical performance of recycled LDPE blends in extrusion systems. Journal of Plastic Film & Sheeting, 25(1) (2009) 39–52.

[18] Wang, H., & Zhao, Y. - Heat transfer modeling of barrel temperature control in plastic extrusion. Polymer Engineering & Science, 48(9) (2008) 1759–1766.

[19] Tadmor, Z., & Gogos, C. G. - Principles of Polymer Processing (2nd ed.). Wiley-Interscience, (2013).

[20] Osswald, T. A., & Hernández-Ortiz, J. P. - Polymer Processing: Modeling and Simulation. Hanser Publishers, (2010).

[21] White, J. L., & Coran, A. Y. - Screw Extrusion: Science and Technology. Hanser, (2009).

[22] Osswald, T. A., & Menges, G. - Materials Science of Polymers for Engineers (2nd ed.). Hanser Publishers, (2003).

[23] Brydson, J. A. - Plastics Materials (7th ed.). Butterworth-Heinemann, (1999).

[24] Rosato, D. V. & Rosato, D. V. - Extruding Plastics: A Practical Guide. Springer, (1997).

[25] Harper, C. A. - Modern Plastics Handbook. McGraw-Hill, (1996).
[26] Strong, A. B. - Plastics: Materials and Processing. Prentice Hall, (1996).
[27] Crawford, R. J. - Plastics Engineering (3rd ed.). Butterworth-Heinemann, (1998).
[28] Chanda, M., & Roy, S. K. - Plastics Technology Handbook (2nd ed.). CRC Press, (1992).
[29] Dym, C. L. - Heat Transfer in Engineering. McGraw-Hill, (1989).
[30] Ghosh, P. - Polymer Science and Technology of Plastics and Rubber. Tata McGraw Hill, (1989).
[31] Schueneman, G. T. - Design of Extrusion Dies. McGraw-Hill, (1987).
[32] Beatty, J. W. - Handbook of Heat Transfer Applications. McGraw-Hill, (1986).