

**EXERGY ASSESSMENT OF THE FRYING PROCESS IN A NOODLE
PRODUCTION PLANT IN PORT HARCOURT, NIGERIA**

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Abstract

This study presents an exergy assessment of the frying process in a noodle production plant located in Port Harcourt, Nigeria. The objective was to evaluate the thermodynamic performance of the major heat transfer equipment involved in the frying operation and identify the major sources of exergy destruction within the system. Thermodynamic and operational data for five consecutive days of continuous plant operation were obtained from plant inventory records and analyzed using conventional and advanced exergy analysis methods implemented in MATLAB. The analysis was performed on the boiler, heat exchanger, and fryer. Results showed that the boiler recorded the highest exergy destruction rate ranging from 432.05 to 433.94 kW, while the heat exchanger recorded exergy destruction rates between 104.91 and 106.41 kW. Advanced exergy analysis revealed that the exergy destruction associated with the fryer was predominantly avoidable, ranging from 0.3800 to 0.3945 kW, whereas that of the boiler was largely unavoidable, ranging from 432.01 to 434.02 kW. The findings indicate that the boiler constitutes the major source of thermodynamic inefficiency in the frying process due to irreversibilities associated with fuel combustion and heat transfer. The study provides useful information for identifying performance improvement opportunities and reducing exergy losses in industrial noodle production systems.

Keywords: Exergy Analysis, Advanced Exergy Analysis, Exergy Destruction, Boiler, Heat Exchanger, Frying Process

1. Introduction

Food processing industries are among the largest consumers of thermal energy worldwide. In noodle manufacturing plants, thermal energy is extensively utilized during steaming, drying and frying operations. The efficiency of these processes significantly affects production cost, energy utilization and environmental sustainability.

Conventional energy analysis based on the First Law of Thermodynamics is useful in determining energy quantities but cannot adequately identify the quality of energy losses occurring within thermal systems. Exergy analysis, based on the Second Law of Thermodynamics, provides a more realistic assessment of system performance by quantifying irreversibilities and identifying opportunities for performance improvement.

Several studies have applied exergy analysis to boilers, heat exchangers and industrial food processing systems. However, limited information exists on exergy assessment of industrial noodle frying systems in Nigeria. This study therefore evaluates the exergy performance of the frying section of a noodle production plant in Port Harcourt, Nigeria.

The objectives of the study are:

To evaluate the exergy performance of the frying system.

To determine exergy destruction rates in the boiler, heat exchanger and fryer.

To identify avoidable and unavoidable exergy destructions.

To identify the major source of thermodynamic inefficiency within the frying system.

2. System Description

The frying system consists of three major heat transfer components:

- Boiler
- Heat Exchanger
- Fryer

The boiler generates superheated steam which supplies thermal energy to the shell-and-tube heat exchanger. The heat exchanger transfers thermal energy from steam to palm oil. The heated palm oil is then supplied to the fryer where the noodle product is fried.

2. Literature Review

Exergy analysis has emerged as a powerful thermodynamic tool for evaluating the performance of energy systems because it considers both the quantity and quality of energy. Unlike conventional energy analysis, which is based solely on the First Law of Thermodynamics, exergy analysis incorporates the Second Law of Thermodynamics to identify irreversibilities and determine the true potential for system improvement. According to Dincer and Rosen (2013), exergy analysis provides a more realistic measure of system performance and serves as an effective tool for promoting energy efficiency and sustainable development.

Boilers are among the most critical thermal components in industrial processes and have been the subject of numerous exergy studies. Kumar et al. (2015) investigated the exergy performance of industrial boilers and reported that combustion processes account for a significant portion of total exergy destruction due to inherent irreversibilities associated with fuel combustion and heat transfer. Similarly, Bathe and Dandge (2017) conducted an energy and exergy assessment of a cogeneration power plant and observed that the boiler represented the largest source of thermodynamic inefficiency within the system. Their findings suggest that improving combustion efficiency can significantly reduce exergy losses and enhance overall plant performance.

In the Nigerian context, Eke et al. (2018) evaluated the performance of a 220 MW thermal power plant and found that steam generation units contributed substantially to overall system irreversibility. The study emphasized the importance of boiler optimization as a means of improving energy utilization and reducing operational losses.

Heat exchangers play an important role in industrial thermal systems by facilitating energy transfer between fluids at different temperatures. However, exergy losses often occur due to finite temperature differences during heat exchange. Orhan Dincer and Rosen (2011) demonstrated that exergy destruction within heat exchangers increases with increasing temperature gradients between the hot and cold streams. Their work highlighted the need for proper heat exchanger design and operation to minimize thermodynamic losses and improve thermal effectiveness.

To provide a deeper understanding of system inefficiencies, researchers have developed advanced exergy analysis techniques. Tsatsaronis and Park (2002) introduced the concept of separating total exergy destruction into avoidable and unavoidable components, thereby enabling engineers to distinguish between realistic and unavoidable performance limitations.

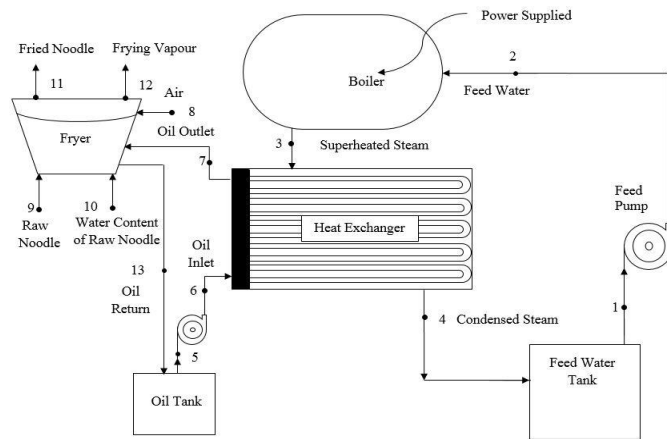
Building on this concept, Morosuk Kelly and Tsatsaronis (2013) expanded advanced exergy analysis by distinguishing endogenous and exogenous exergy destructions, providing additional insight into the interactions among system components and their contributions to overall inefficiency.

The application of exergy analysis in food processing systems has also received considerable attention. Erbay and Hepbasli (2013; 2014) applied conventional and advanced exergy analyses to food drying systems and reported that significant reductions in exergy destruction could be achieved through improved equipment design and optimized operating conditions. Similarly, Buhler Nguyen Jensen and Elmegaard (2016) demonstrated the effectiveness of advanced exergy analysis in identifying improvement opportunities within industrial food-processing facilities.

Specific studies on frying operations have shown that frying processes are associated with considerable thermodynamic losses. Genc and Hepbasli (2015) evaluated the performance of a potato crisp frying process and reported that significant exergy destruction occurs due to heat transfer across finite temperature differences between the heating medium and the product. Their findings indicated that process optimization and improved thermal management could significantly enhance system efficiency.

Although previous studies have extensively investigated exergy destruction in boilers, heat exchangers, power plants, drying systems, and food-processing operations, there is limited information on the exergy performance of industrial noodle frying systems in Nigeria. Furthermore, few studies have applied advanced exergy analysis to identify avoidable and unavoidable exergy destructions within such systems. Therefore, this study seeks to evaluate the exergy performance of the frying section of a noodle production plant in Port Harcourt, Nigeria, with emphasis on determining exergy destruction rates and identifying opportunities for thermodynamic performance improvement.

Figure 1: Schematic Diagram of Frying System



3. Materials and Methods

3.1 Plant Data

The study was conducted using operational data obtained from the production records of the noodle plant for five consecutive days of operation. The major design parameters of the system are summarized in Table 1.

TABLE 1: DESIGN PARAMETER DATA OF THE BOILER

Parameters	Value
Rated steam output	1t/h(0.3kg/s)
Rated Steam temperature	194°C (467K)
Rated Feed water temperature	105°C (378)
Rated working pressure	0.5MPa (5bar)
Fuel consumption rate	70.1Nm ³ /h (0.038kg/s)
Fuel	LNG, LPG

Source: Facilities log book containing data from the boiler and heat exchanger unit of the noodle production plant of Dufil Prima Foods Plc, Port Harcourt

TABLE 2: DESIGN PARAMETER DATA OF THE HEAT EXCHANGER

Parameters	Hot Fluid in Shell Side	Cold Fluid in Tube Side
Working Fluid	Steam	Frying Oil (Palm Oil)
Mass Flow	0.2kg/s	25.2kg/s
Inlet/Outlet Temperature	220°C/180°C	110°C/160°C
Design Pressure	0.8MPa (8bar)	0.3MPa (3bar)
Tube Length	-	2.850m
Tube Diameter	-	0.025m
Number of Tubes	-	20
Shell Diameter	0.219m	-
Shell Length	3.180m	-

Source: Facilities log book containing data from the boiler and heat exchanger unit of the noodle production plant of Dufil Prima Foods Plc, Port Harcourt.

TABLE 3. DESIGN PARAMETER DATA OF THE FRYER

Parameters	Value
Material	Stainless steel
Cross sectional area	1000 x 780 x 650mm

Source: Facilities log book containing data from the boiler and heat exchanger unit of the noodle production plant of Dufil Prima Foods Plc, Port Harcourt.

3.2 Exergy Analysis

The physical exergy of a stream is calculated using:

$$Ex = (h - h_0) - T_0(s - s_0)$$

The exergy balance for each component was determined using:

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_D$$

The exergy efficiency was calculated using:

$$\eta_{ex} = \frac{\dot{E}_{product}}{\dot{E}_{fuel}}$$

where:

Ex = Exergy (kW)

$\dot{E}_D$ = Exergy destruction rate (kW)

η_{ex} = Exergy efficiency

3.3 Advanced Exergy Analysis

Advanced exergy analysis separates total exergy destruction into:

Avoidable exergy destruction

Unavoidable exergy destruction

The avoidable component represents the actual improvement potential available within the system.

TABLE 4: THERMODYNAMIC DATA OF THE FRYING SYSTEM

State	Fluid/ Noodle	Day 1		Day 2		Day 3		Day 4		Day 5	
		Temperature (k)	Pressure (bar)	Temperature (k)	Pressure (bar)	Temperature (k)	Pressure (bar)	Temperature (k)	Pressure (bar)	Temperature (k)	Pressure (bar)
1	water	319	0.1	319	0.1	319	0.1	319	0.1	319	0.1
2	water	393	5	393	5	393	5	393	5	393	5
3	Steam	467	5	466	5	460	5	457	5	456	5
4	Steam	342	0.1	340	0.4	339	0.7	341	0.3	339	0.6
5	Palm oil	338	0.1	338	0.1	338	0.1	338	0.1	338	0.1
6	Palm oil	338	0.1	338	0.1	338	0.1	338	0.1	338	0.1
7	Palm oil	460	3.3	458	3.3	455	3.3	454	3.3	450	3.3
8	Air	433	1	433	1	433	1	433	1	433	1
9	Noodle	343	1	343	1	343	1	343	1	343	1
10	Water	343	1	343	1	343	1	343	1	343	1
11	Noodle	433	1	438	1	450	1	453	1	455	1
12	Steam	433	1	438	1	450	1	453	1	455	1
13	Palm oil	433	1	438	1	450	1	453	1	455	1

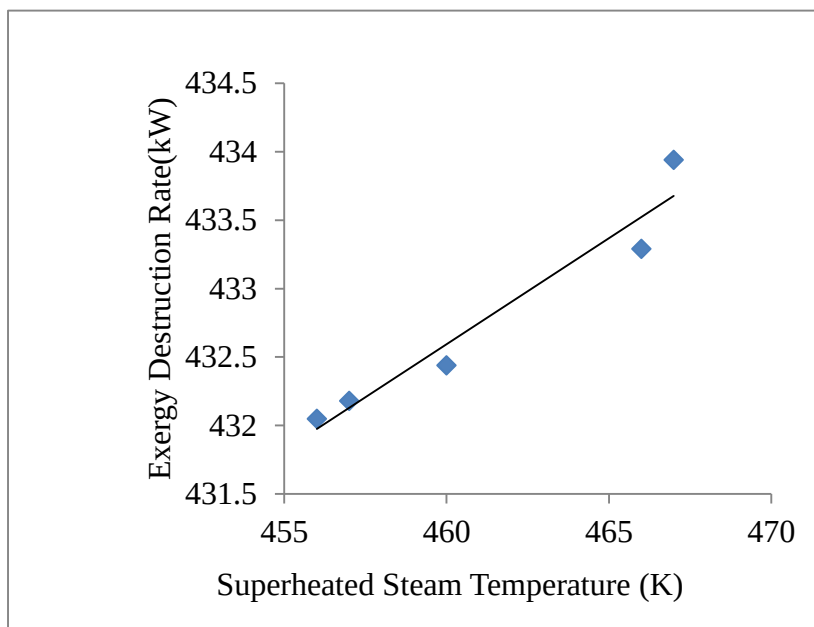
4. Results and Discussion

TABLE 5: EXERGY PERFORMANCE ANALYSIS OF COMPONENTS

Time (Day)	Component	Superheated Steam Temperature (K)	Exergy Destruction Rate (kW)	Exergy Efficiency (%)
1	Boiler	467	433.94	33.62
	Heat Exchanger		106.41	51.83
	Fryer		29.41	58.30
2	Boiler	466	433.29	33.29
	Heat Exchanger		105.90	50.72
	Fryer		29.06	57.48
3	Boiler	460	432.44	33.15
	Heat Exchanger		105.68	48.82
	Fryer		28.83	57.39
4	Boiler	457	432.18	33.11
	Heat Exchanger		105.45	47.96
	Fryer		28.62	56.95
5	Boiler	456	432.05	33.09
	Heat Exchanger		104.91	47.42
	Fryer		28.43	56.51

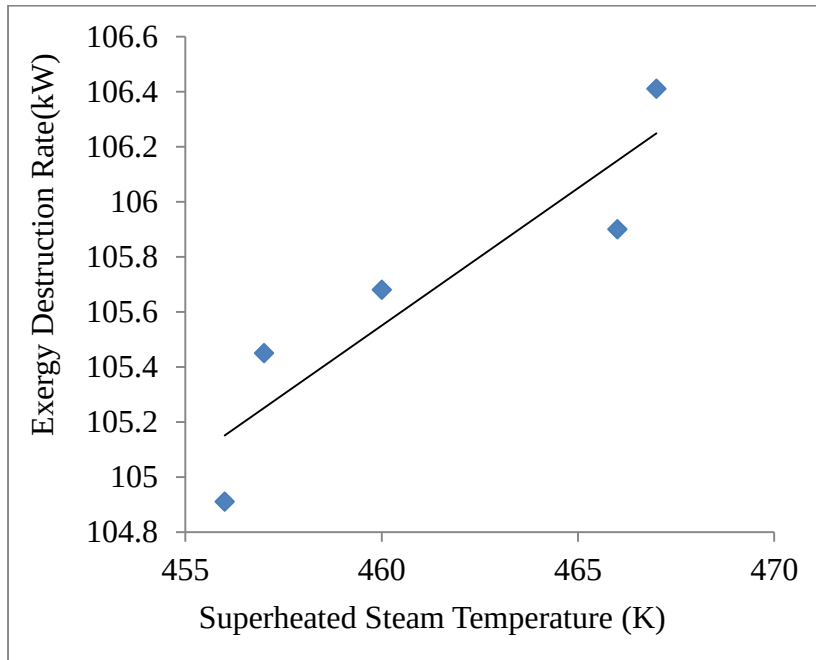
The boiler exhibited the highest exergy destruction throughout the study period. This indicates that combustion-related irreversibilities constitute the dominant source of thermodynamic inefficiency within the frying system.

Figure 2: Exergy Destruction rate in the boiler



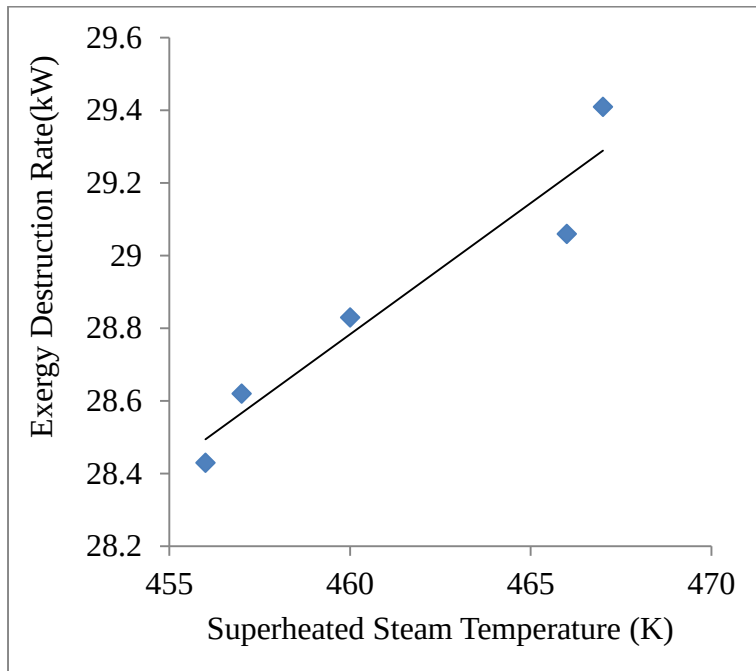
Graph of Exergy Destruction Rate of the Boiler Vs Superheated Steam Temperature

Figure 3: Exergy Destruction in the Heat Exchanger



Graph of Exergy Destruction Rate of the Heat Exchanger Vs Superheated Steam Temperature

Figure 4: Exergy Destruction in the fryer



Graph of Exergy Destruction Rate of the Fryer Vs Superheated Steam Temperature

4.2 Boiler Exergy Performance

The boiler contributed more than 75% of the total exergy destruction in the system. The large exergy destruction observed in the boiler can be attributed to:

Combustion irreversibility

Heat transfer across finite temperature differences

Flue gas losses

The gradual increase in exergy destruction during the five-day operation suggests progressive performance deterioration possibly caused by fouling and operational deviations.

The present findings are consistent with those reported by Kumar et al. (2015), who identified combustion processes as the dominant source of exergy destruction in industrial boilers. Similar observations were reported by Bathe and Dandge (2017), who found that boiler units contributed the largest share of thermodynamic inefficiencies in cogeneration systems. In the Nigerian context, Eke et al. (2018) also reported substantial exergy losses in steam generation units of thermal power plants. The agreement between the present study and previous investigations confirms that combustion-related irreversibilities remain the primary cause of exergy destruction in thermal systems.

4.3 Heat Exchanger Exergy Performance

The heat exchanger recorded the second highest exergy destruction. Although lower than that of the boiler, its exergy losses were significant and largely associated with temperature gradients between the steam and palm oil streams.

The increase in exergy destruction observed during operation may be linked to fouling on the heat transfer surfaces.

4.4 Advanced Exergy Analysis

TABLE 6: AVOIDABLE AND UNAVOIDABLE EXERGY DESTRUCTION ANALYSIS OF COMPONENTS

Time (Day)	Component	Superheated Steam Temperature (K)	Avoidable Exergy Destruction Rate (kW)	Unavoidable Exergy Destruction Rate (kW)	Total Unavoidable Exergy Destruction Rate (kW)
1	Boiler	467	0.077	434.02	434.097
	Heat Exchanger		0.0047	106.405	106.4097
	Fryer		0.3945	29.805	30.1995
2	Boiler	466	0.074	433.22	433.294
	Heat Exchanger		0.0044	105.89	105.8944
	Fryer		0.3923	28.667	29.0593
3	Boiler	460	0.068	432.37	432.438
	Heat Exchanger		0.004	105.68	105.684
	Fryer		0.3911	28.435	28.8261
4	Boiler	457	0.05	432.13	432.180
	Heat Exchanger		0.0038	105.44	105.4438
	Fryer		0.3854	28.235	28.6204
5	Boiler	456	0.04	432.01	432.050
	Heat Exchanger		0.003	104.90	104.903
	Fryer		0.3800	28.05	28.4300

The results indicate that the boiler exergy destruction is largely unavoidable under present technological conditions. Conversely, the fryer exhibits predominantly avoidable exergy destruction and therefore offers greater opportunities for performance improvement.

The results of the advanced exergy analysis support the findings of Tsatsaronis and Park (2002), who demonstrated that separating exergy destruction into avoidable and unavoidable components provides valuable information for system improvement. The predominance of avoidable exergy destruction in the fryer indicates a greater potential for operational enhancement, while the largely unavoidable exergy destruction in the boiler suggests that improvements may be constrained by existing technological limitations.

Avoidable and Unavoidable Exergy Destruction

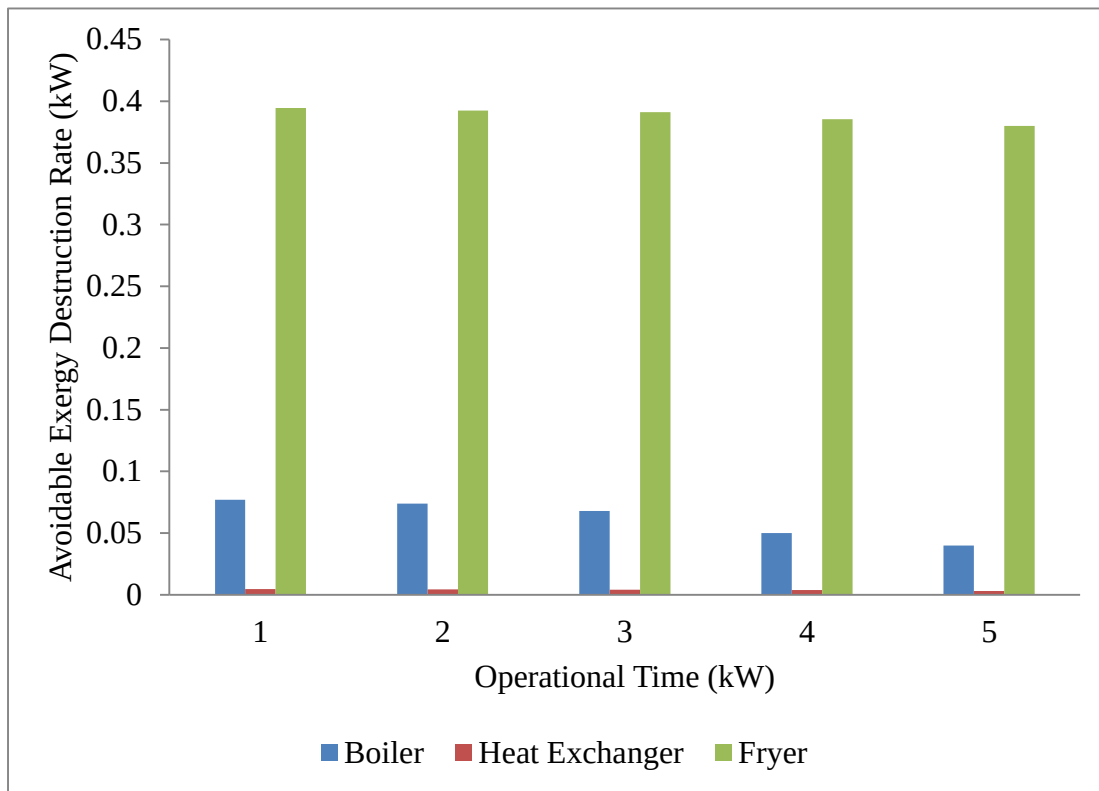


Fig. 5: Avoidable exergy destruction rate vs operational time

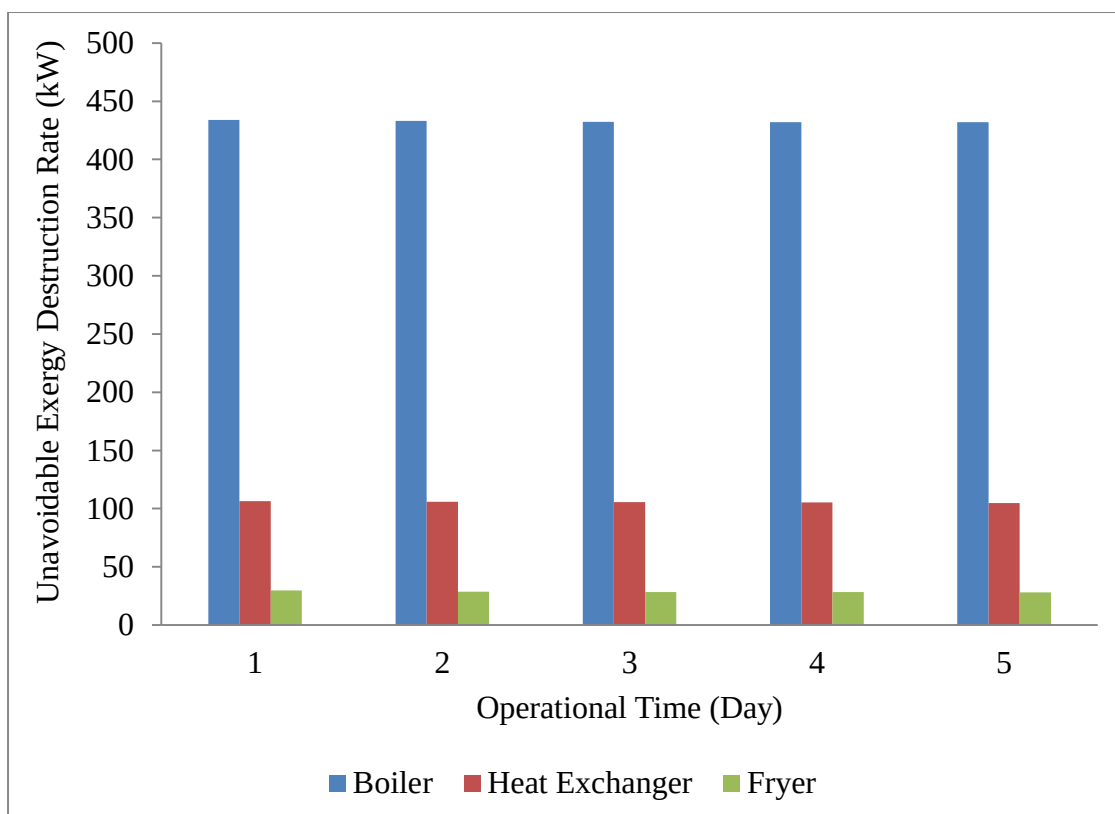


Fig. 6: Unavoidable exergy destruction rate vs operational time

4.5 Discussion

The findings demonstrate that the boiler is the major contributor to system irreversibility. Similar observations have been reported in studies involving steam generation systems where combustion processes account for the largest proportion of exergy destruction.

The advanced exergy analysis further shows that improvement efforts should focus on reducing avoidable exergy destruction within the fryer while maintaining optimum operating conditions in the boiler.

5. Conclusions

An exergy assessment of the frying process in a noodle production plant was conducted using operational data collected over five consecutive days.

The major findings are:

- The boiler recorded the highest exergy destruction rate, ranging from 432.05 to 433.94 kW.
- The heat exchanger recorded exergy destruction rates ranging from 104.91 to 106.41 kW.
- The fryer exhibited predominantly avoidable exergy destruction.
- The boiler remains the primary source of thermodynamic inefficiency within the frying system.
- Future performance improvement strategies should focus on minimizing combustion irreversibility and maintaining optimal boiler operating conditions.

NOMENCLATURE

Symbol	Description	Unit
E_x	Exergy	kW
$E_{x,D}$	Exergy destruction	kW
T	Temperature	K
P	Pressure	bar
h	Specific enthalpy	kJ/kg
s	Specific entropy	kJ/kg·K
η_{ex}	Exergy efficiency	%
$\dot{m}$	Mass flow rate	kg/s

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