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Energy utilization and exergy indices: A comparative analysis of a convective (Electric/gas) dryer

John Chikaelo Okeke *, Calistus Princewill Odeh, Augustine Madumere Uzodinma, Chibuzo Ndubuisi Okoye, and Onyeka Noel Anyali

Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Nigeria.

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Abstract

This study investigates Energy utilization (EU) and Exergy indices of a convective dryer utilizing electric and gas heat sources at temperatures of 45 °C and 60 °C, with a drying air velocity of 3m/s. Energy utilization result indicate that at 45 °C, the minimum energy utilization (EU) for the electric heat source was 0.8862 kJ/s, while the gas heat source recorded a minimum of 1.1 kJ/s. At 60 °C, the maximum EU values were 3.87 kJ/s for electric and 4.2 kJ/s for gas. A clear trend was observed, showing an increase in EU with rising temperature. Exergy efficiency comparison consistently showed superior performance of gas, with recorded efficiencies of 45.5% for electric at 45 °C, 53.3% for gas, 62% for electric at 60 °C, and 70.1% for gas. The study suggests optimization opportunities, noting higher potential for improvement with electric at both temperatures. The Exergy Sustainability Index indicated gas's better utilization of available exergy at 2.14 and 3.344 for 45 °C and 60 °C, respectively, compared to electric at 1.835 and 2.63 for 45 °C and 60 °C, respectively. In conclusion, the study recommends gas heat source for superior efficiency in drying African mud Catfish.

Keywords: Energy Utilization; Exergy Indices; Electric/Gas Heat Source; Convective Dryer

1. Introduction

Drying, a crucial tool in preserving food, relies on various methods like sun drying in regions like Nigeria. It's also a thermodynamic process of heat and mass transfer. It involves the simultaneous transfer of heat to food for evaporation of water and the transport of water vapor formed away from the food [1]. Convective hot air drying has been predominantly used in many industries such as agro industries and pharmaceutical industries. Some of its advantages include low production and operation costs, efficient surface water removal, good physicochemical, nutritional and functional properties [2].

Energy consumption is a key engineering and technological challenge in industrial drying processes [3]. The substantial energy demand of most industrial dryers leads to increased operational costs, making the drying process expensive. Energy and exergy analyses of a drying process offer insights into energy savings and optimal process conditions [3]. Energy analysis provides a quantitative measure of the energy needed for a system, while exergy analysis offers a qualitative assessment of the useful energy utilized by the system [4]. Exergy is consumed or destroyed during the drying process (i.e., it is irreversible) [5]. It evaluates the quality of energy available in various components of drying systems, which is crucial for designing sustainable industrial drying systems [6]. Moreover, exergy analysis is essential for assessing energy consumption, energy conversion efficiency, the environmental impact of energy resource utilization, and the operational cost of a drying process.

* Corresponding author: Okeke J.C.

Many studies have been carried out on gas and electric heat source convective dryer and also in the area of energy and exergy analysis. Okeke et al [7] studied the comparative analysis of a convective electric/gas convective dryer at 45 °C and 60 °C with focus on the heat flow and drying performance with results showing that the gas had a higher drying rate, higher effective diffusivity of 8.9×10^{-8} m^2/s to 1.42×10^{-7} m^2/s for both temperatures and also higher activation energy of 42.59kj/mol. The page model gave the best fit for the drying kinetic modeling. Akbulut and Durmus [8] analyzed the drying process of mulberry slices using a forced solar dryer and found that as the air mass flow rate increased, the energy utilization ratio and exergy loss decreased, while exergy efficiency improved. Aviara et al. [3] found that for cassava starch in a tray dryer, both energy efficiency and exergy efficiency increased with rising temperature, while exergy loss also showed an increase.

The results from these studies showed that Energy utilization, exergy inflow, exergy outflow, exergy efficiency, and exergy loss were all affected by the drying temperatures, air velocity and the drying material. Despite similar effects of drying parameters being observed in the literature, different values for energy and exergy assessments were reported, even when the same type of dryer and different heat sources were used. This shows that energy and exergy requirement for materials and heat sources differ. It has been shown that the values for energy and exergy indices are necessary for optimization of convective dryers in industries. There are few literatures comparing this indices for a single convective dryer having electric and gas heat source. Therefore the objective for this study is to compare the Energy Utilization and Exergy indices for a convective dryer powered by a dual (gas/electric) heat source at 45 °Cand 60 °Cusing an African mud catfish *(Clarias gariepinus*) as the drying material

2. Materials and Methods

2.1. Sample preparation

The African mud catfish (Clarias gariepinus) obtained from the local market in Anambra, Nigeria was used for this study. The specie is a popular delicacy among the low- and middle-income earners and vary in size, and relatively cheap and affordable. The fish was degutted, washed very well with clean water, brined and set for drying. The fish was then arranged in the mesh tray outside the drying chamber and left to drain for about 5-8 minutes

2.2. Experimental Setup

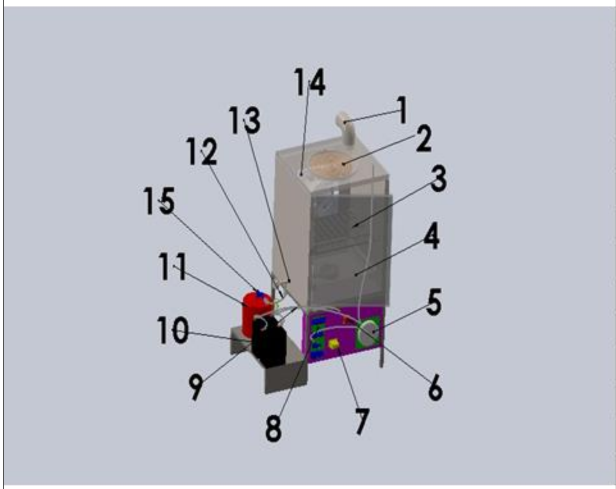
In this experiment, a 0.42m by 0.39m by 0.39m (HLB) hybrid gas/electric convective dryer made of stainless steel insulated with fiberglass, characterized by its capability to operate at various temperatures (range of 0 – 399K) and blower speeds (2m/s – 7m/s), was employed. The fundamental components of this dryer includes a STEL E5EM thermostat equipped with a sensor to regulate the temperature of the electric coil, a blower responsible for distributing heat from the source to the drying chamber, a mesh tray designated for sample placement, and a gas control system comprising a solenoid valve, igniter, thermostat, temperature and humidity sensors at the inlet and outlet of the dryer.

2.3. Electric control system

The electric system incorporates a heating element of 1.8kw and a distinct temperature regulator control mechanism. Here, the user inputs the desired control temperature, and the thermostat, upon sensing the temperature, transmits a signal to the contractor. The contractor then modulates the heater, cycling it on and off at predetermined intervals in accordance with the set temperature.

2.4. Gas control system

Conversely, the gas system encompasses a control section where the user inputs both the desired temperature and the ignition time. Subsequent to the temperature input, the thermostat dispatches a signal to the solenoid valve, prompting it to open. Following a specific duration, determined by the set ignition time (8 seconds, in this instance), the igniter activates, initiating combustion within the burner.



Number	Component Name
1	Exhaust
2	Heating Element
3	Fish Tray
4	Oil Tray
5	Gas Control
6	Power Button
7	Blower Control
8	Electric Control
9	Electric Cable
10	Battery
11	Gas Cylinder
12	Gas Hose
13	Burner
14	Blower
15	Solenoid Valve

Figure 1 Schematic view of the developed convective dryer

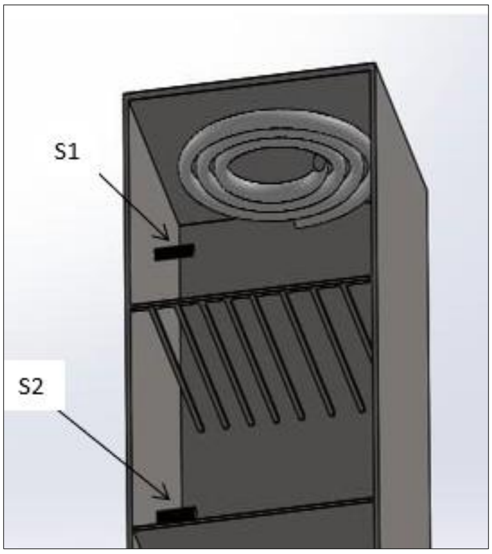


Figure 2 Exploded view of the dryer showing the sensors (S1 and S2)

Where S1 is Temperature and Humidity sensor 1, and S2 is the Temperature and Humidity sensor 2

2.5. Drying operation

The study was carried out in Awka, Anambra state using a dual powered convective dryer (a gas powered and electrical powered kiln) at drying air temperatures of 45 °C and 60 °C, drying air velocity of 3m/s. The parameters selected were based on submissions from literatures Ikrang et al [9], Kenechi et al [10]. Firstly the initial moisture content was gotten by drying the fish in the dryer at 105 °C for 24 hours until it is bone dried (there was no significant change in weight after two successive intervals). The dryer was powered and left for some time to attain the desired drying conditions (Temperatures of 45 °C and 60 °C), the pretreated fish was placed on the tray mesh and fed into the oven, the sample was extracted from the oven and weighed at time interval of 15mins for the first 1 hour and 30 mins for the remaining time to determine the weight loss and moisture content until a safe moisture content of 10% or less was attained. The Virgo digital electronic lab weighing scale with accuracy of 0.1g and maximum capacity 2000g was kept very close to dryer and weighing period of 20s was maintained. The dryer also has an automatic data logger which consists of the following parts; an Arduino interfaced with a temperature sensor (10K NTC temperature sensors, temperature range of −50 to 200 °C, accuracy ±0.2 °C), a humidity sensor (DHT11 humidity sensor, humidity range of 10 to 100%, accuracy ± 2%), and an LCD screen where measurements are recorded and observed at intervals. Two temperature and humidity sensors were used; one temperature and humidity sensor was placed at drying air inlet, and another was placed at the air exit point. These values were recorded at 10 min intervals on the LCD screen of the data logger.

2.6. Energy and Exergy Analysis

2.6.1. Energy analysis

The flow was assumed to be steady and the first law of thermodynamics was adopted. The energy utilization was calculated throughout the fish drying process using models proposed by Aviara *et al* [3].

The conservation of mass for the dry air

$$\sum \dot{m}_1 = \sum \dot{m}_2 \text{ .... (1)}$$

Where: $\dot{m}_1$ is the inlet mass flow rate (kg·s⁻¹); $\dot{m}_2$ is the outlet mass flow rate (kg·s⁻¹).

Energy balance equation

$$Q - W = \Delta U = \sum \dot{M}_{A2}\left[h_2 + \frac{V_2^2}{2}\right] - \sum \dot{M}_{A1}\left[h_1 + \frac{V_1^2}{2}\right] \text{ .... (2)}$$

Assuming no resultant motion, equal mass flow rate and no mechanical work during the drying process. According to Aviara *et al* [3] the equation becomes

$$Q = \dot{M}_A(h_1 - h_2) \text{ .... (3)}$$

$$\text{Where } \dot{M}_A = \rho_A \dot{V}_A \text{ .... (4)}$$

$$h = C_{pA}T_{dA} + Hh_{sat} \text{ ....(5)}$$

$$C_{pA} = 1.003 + 0.00005T_{dA} \text{ .... (6)}$$

2.6.2. Energy Utilization

The investigation encompassed a thorough examination of energy usage (EU), inflow and outflow of exergy, and efficiency metrics for two distinct heat sources in the dryer. Temperature data was collected using 10K NTC temperature sensors, while relative humidity readings were obtained via DHT22 humidity sensors at both the dryer's inlet and outlet. These parameters played a crucial role in establishing the temperature and humidity conditions at the inlet and outlet.

The energy utilization for the dryer was calculated from the equation as given by Abiodun et al [11]

$$EU = \dot{M}_A(h_1 - h_2) \text{ .... (7)}$$

2.7. Exergy analysis

This analysis was carried out using the second law of thermodynamics. It shows that the amount of heat energy supplied to the system which is used in doing work is not conserved; it suffers an amount of degradation. The Mathematical equation as proposed by Aviara *et al* [3] and Abiodun et al [11] is given in eqn 8

$$EX = C_p\left[(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right] \text{ .... (8)}$$

For calculating the exergy inflow, exergy outflow and exergy loss depending on the drying chamber's inlet and outlet temperatures we have:

Exergy loss = Exergy inflow – Exergy outflow

$$\sum EX_L = EX_1 - \sum EX_2 \text{ .... (9)}$$

EX_L, EX_1, EX_2 are exergy loss, exergy inflow and outflow, respectively (J·s⁻¹).

$$EX_1 = C_p \left[(T_1 - T_\infty) - T_\infty \ln \frac{T_1}{T_\infty}\right] \text{......................} (10)$$

Substituting the value for C_p we have,

$$EX_1 = 1.003 + 0.00005T_1 \left[(T_1 - T_\infty) - T_\infty \ln \frac{T_1}{T_\infty}\right] \text{..........} (11)$$

$$EX_2 = C_p \left[(T_2 - T_\infty) - T_\infty \ln \frac{T_2}{T_\infty}\right] \text{...........} (12)$$

$$EX_2 = 1.003 + 0.00005T_2 \left[(T_2 - T_\infty) - T_\infty \ln \frac{T_2}{T_\infty}\right] \text{..............} (13)$$

T_1, T_2 and T_∞ are inlet, outlet and ambient temperatures respectively

$$Exergy\ Efficiency = qaA \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow}$$

$$\text{Or } Exergy\ Efficiency = 1 - \frac{Exergy\ loss}{Exergy\ inflow}$$

$$\eta_{EX} = 1 - \frac{EX_L}{EX_1} \times 100 \text{ ....} (14)$$

η_{EX} *is the exergy efficiency*

2.8. Improvement Potential

Improvement potential in exergy analysis is the amount of additional useful work that can be extracted from a system by implementing design modifications or operational improvements. It was calculated for the fish drying process using Equation as proposed by Aviara *et al* [3], and Abiodun *et al* [11]

$$I_p = \left(1 - \left(1 - \left(\frac{EX_L}{EX_1}\right)\right)\right) \times (EX_1 - EX_2) \text{..........} (15)$$

2.8.1. Exergy Sustainability Index (ESI)

It was calculated using Equation 3.37

$$ESI = \frac{1}{1 - EX_{eff}} \text{ ....} (16)$$

3. Results and Discussions

3.1. Energy Utilization

From Fig 2 the minimum EU recorded for the electric heat source was 0.8862 kJ/s at 45 °C, whereas the gas heat source showed a minimum of 1.1 kJ/s at the same temperature. At 60 °C, the maximum EU values were observed: 3.87 kJ/s for electric and 4.2 kJ/s for gas. Noteworthy is the trend depicting an increase in EU with temperature rise, aligning with findings by other researchers. Akpinar [4] documented EU values ranging between 190 to 3,733 J/s for convective drying of red peppers across temperatures of 55 to 70 °C. Similarly, Abiodun [11] reported EU values of 5.47 to 114.36 W during the drying of Okra for temperatures spanning 50 to 70 °C, showing an upward trend in EU values with higher drying air temperatures.

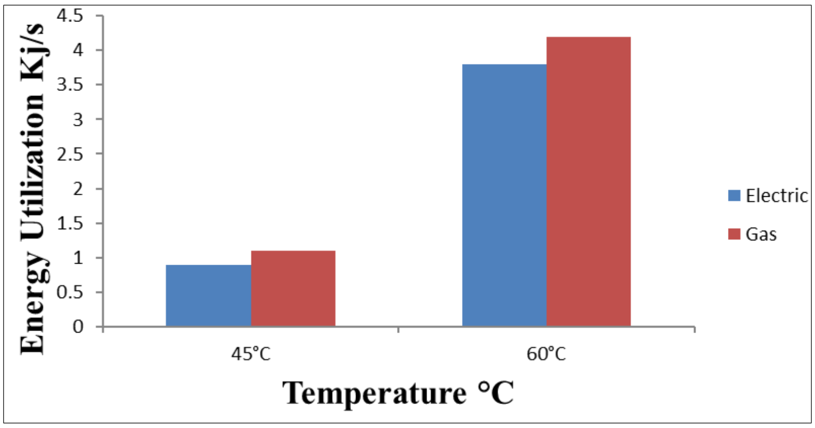


Figure 3 A chart of Energy Utilization against Temperature

3.2. Exergy Analysis

The investigation encompassed an exergy analysis aimed at scrutinizing the performance dynamics of heat sources operating within the dryer system. This rigorous analysis involved precise measurements of exergy inflow, outflow, and losses at discrete temperatures of 45 °Cand 60 °C, focusing on both electric and gas heat sources. These measurements were meticulously acquired through the utilization of highly accurate instrumentation.

At the temperature threshold of 45 °C, the electric heat source exhibited quantifiable exergy values: 1.33 kJ/s (inflow), 0.605 kJ/s (outflow), and 0.725 kJ/s (loss), while the gas heat source showed respective figures of 1.5 kJ/s (inflow), 0.8 kJ/s (outflow), and 0.7 kJ/s (loss).

Elevating the temperature to 60 °C led to an increase in exergy values for both heat sources: the electric source manifested figures of 4.41 kJ/s (inflow), 2.73 kJ/s (outflow), and 1.68 kJ/s (loss), whereas the gas source displayed values of 5.2 kJ/s (inflow), 3.65 kJ/s (outflow), and 1.55 kJ/s (loss).

This analysis unveiled a consistent trend of amplified exergy losses in tandem with temperature increments for both the electric and gas heat sources. This observation points toward a heightened dissipation of useful energy at elevated temperatures.

Interestingly, despite operating at identical temperatures, the gas heat source demonstrated lower exergy losses compared to its electric counterpart. This discernment suggests a relatively superior efficiency in energy utilization by the gas heat source under analogous operational conditions, consequently leading to reduced losses.

Parallel findings have been documented by prior research endeavors. For instance, Hassan *et al* [12] observed analogous trends in the Paper Drying Process, noting increased exergy losses correlating with rising drying air temperatures. Similarly, Kenechi *et al* [10] and Erdem *et al* [13] reported comparable observations in their investigations of yam starch and fish drying processes respectively, illustrating a consistent rise in exergy losses with escalating drying air temperatures.

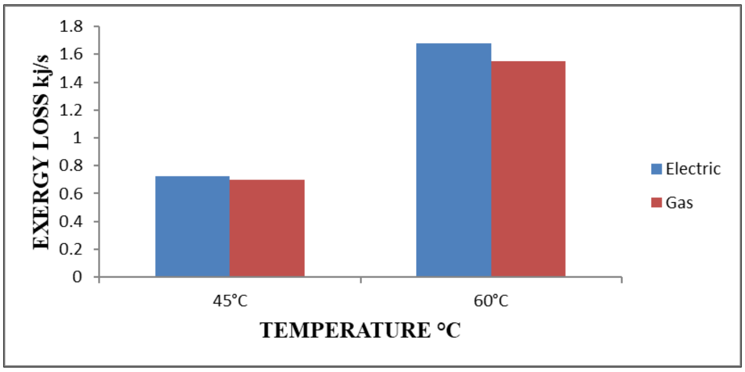


Figure 4 A chart of Exergy loss against Temperature

3.2.1 Exergy Efficiency

Exergy Efficiency at 45 °C: From Fig 4, for the electric source, the recorded exergy efficiency stood at 45.5%, whereas the gas source exhibited an efficiency of 53.3% at this temperature.

Exergy Efficiency at 60 °C: From Fig 4, the electric source displayed an increased exergy efficiency of 62%, while the gas source demonstrated a higher efficiency of 70.1%.

The analysis highlights a consistent trend where exergy efficiency shows an increase with rising temperature for both electric and gas heat sources. This indicates a more effective utilization of energy as temperatures escalate. Notably, the exergy efficiency was consistently higher for the gas source at both 45 °Cand 60 °C. This suggests a comparative advantage of the gas heat source in effectively converting energy into useful work, resulting in higher efficiencies compared to the electric source at similar operating temperatures. The observed trend corroborates prior studies. For instance, Erdem *et al* [13] investigation into fish drying revealed a parallel increase in exergy efficiency with rising temperature.

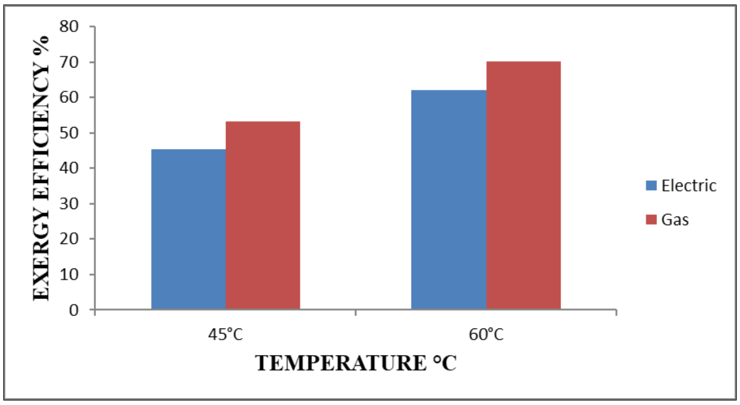


Figure 5 Exergy Efficiency against Temperature

3.2.2 Improvement Potential

From Fig 5 at 45 °C, the improvement potential for the electric heat source was calculated to be 0.395, indicating a significant potential for efficiency enhancement. Conversely, the gas heat source at the same temperature exhibited an improvement potential of 0.33, suggesting a marginally lower scope for optimization. At the elevated temperature of 60 °C, the electric heat source demonstrated an improvement potential of 0.64, showcasing a notable increase in optimization possibilities. Simultaneously, the gas heat source at 60 °C exhibited an improvement potential of 0.462, suggesting a moderate potential for efficiency enhancement compared to the electric source. The higher Improvement Potential values for the electric is because of a higher efficiency value for the gas source as compared to the electric. Aghbashlo *et al* [6] and Erbay & Icier [14] published similar findings that IP increases with increase in temperature on the drying of encapsulated fish oil and olive leaves, respectively. Aghbashlo *et al* [6] identified the rates of the improvement potential to be within the range of 13.28–33.07% of the total input exergy for the fluidized spray drying of fish oil.

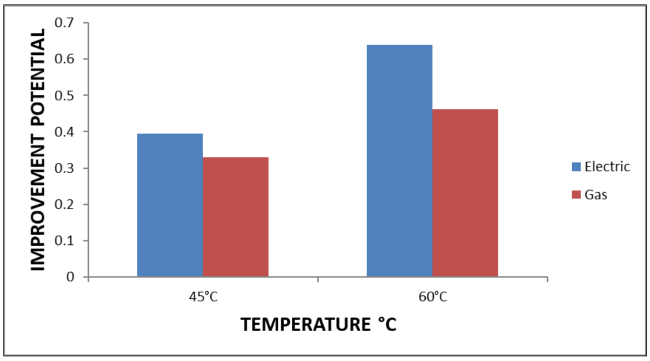


Figure 6 A chart of Improvement Potential vs Temperature

3.2.3 Exergy Sustainability Index (ESI)

Fig 7 shows the effect of drying air temperature and heat source on the sustainability index. The sustainability index increases with increase in temperature for both heat sources. The fig shows that at the same temperature the gas had a higher ESI meaning that the gas heat source used more available exergy as compared to the electric. At 45 °C,The gas and electric heat source recorded 2.14 and 1.835 ESI respectively while at 60 °C, 2.63 and 3.344 ESI was recorded for the electric and gas respectively. Abiodun *et al* [11] also recorded an increase in ESI with increase in temperature.

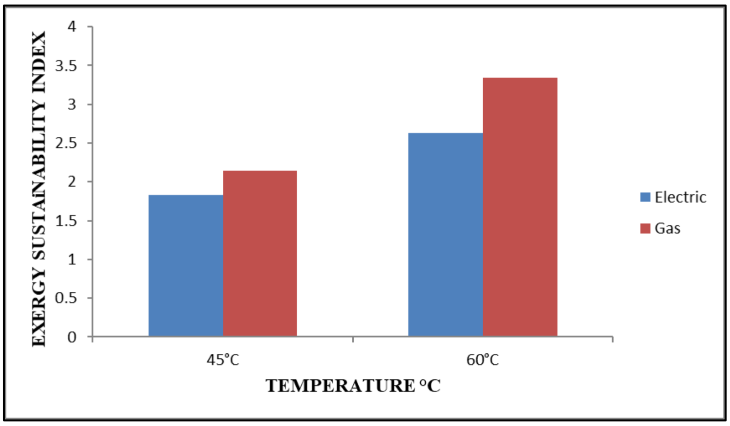


Figure 7 A chart of Exergy sustainability Index vs Temperature

4. Conclusion

The study focused on the comparative analysis of energy utilization, exergy analysis (exergy efficiency, improvement potential, and sustainability index) for electric and gas heat sources at two distinct temperature levels—45 °Cand 60 °C. The findings reveal a general trend of increased energy utilization with rising temperature for both heat sources, which aligns with existing research. Specifically, the gas heat source demonstrated consistently higher energy utilization, exergy efficiency, and sustainability index compared to the electric heat source, signifying its superior performance under similar operational conditions. Exergy analysis at both temperatures unveiled an increase in exergy inflow, outflow, and loss with a temperature rise, highlighting a greater dissipation of useful energy at elevated temperatures. Moreover, exergy efficiency exhibited a marked improvement as temperature increased for both heat sources, with the gas source outperforming the electric source in terms of energy conversion into useful work.

The improvement potential at each temperature point suggests the gas heat source has a relatively lower scope for enhancement compared to the electric source, particularly at higher temperatures. The sustainability index further reinforces the superior efficiency of the gas heat source, which used more available exergy to produce higher sustainability values than the electric source at both temperature levels. These observations corroborate prior research findings and underscore the advantages of the gas heat source for applications requiring higher energy efficiency and sustainability.

Recommendations

Given the higher improvement potential values, there exists a considerable scope for optimizing the electric heat source to improve its efficiency. This could involve improving the design or utilizing more energy-efficient components.

Advanced machine learning techniques such as Support Vector Machines (SVM), Artificial Neural Networks (ANN), or Gradient Boosting can be applied to predict not only exergy efficiency but also other parameters like energy utilization and exergy loss across various temperatures and humidity levels. These methods can be trained with larger datasets to improve accuracy and predict outcomes for conditions not directly observed in the experimental setup.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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