Iraqi Journal of Industrial Research, Vol. 12, No. 1 (2025)

Open Access

Iraqi Journal of Industrial Research (IJOIR)

Journal homepage: http://ijoir.gov.iq

Evaluation of Carbon Dioxide Emissions from Al-Mussaib Thermal Power Plant Using HYSYS Software

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Article information

Article history:
Received: October, 30, 2024
Accepted: December, 16, 2024
Available online: June, 14, 2025

Keywords:
CO_2 emissions,
Fuel consumption,
Thermal power plant,
Thermal efficiency,
HYSYS software

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DOI:
https://doi.org/10.53523/ijoirVol12I1ID533

Abstract

Al-Mussaib Thermal Power Plant faces critical challenges of excessive fuel consumption, leading to significant CO_2 emissions and reduced operational efficiency. These inefficiencies are primarily attributed to outdated equipment, low boiler efficiency, and inadequate maintenance, posing environmental and economic concerns. This study employs HYSYS software to analyze plant performance and propose operational improvements to enhance efficiency and sustainability. The analysis reveals that a specific fuel consumption (SFC) of 0.24 kg/kWh for 155 MW results in CO_2 emissions of 0.75 kg/kWh, while optimal operation requires 0.31 kg/kWh of specific fuel resulting in CO_2 emissions of 0.95 kg/kWh. Similar inefficiencies are evident at higher capacities, such as 205 MW, further underscoring the need for upgrades and regular maintenance. At (155 MW), actual efficiency is only 27%, highlighting substantial room for improvement. Targeted operational adjustments, including regular maintenance, can optimize energy conversion, minimize fuel waste, and reduce emissions. Notably, as at a 70% load, the gap between actual and design fuel consumption narrows from 4.2 kg/s to 2.2 kg/s, reflecting improved efficiency at higher operational loads. Operating under optimized conditions not only reduces unnecessary fuel consumption but also supports sustainable and cost-effective power generation. This study emphasizes the importance of addressing inefficiencies to reduce environmental impact and enhance the operational viability of thermal power plants.

1. Introduction

As global energy demands continue to rise, steam plants remain a vital component of the energy mix, especially in regions dependent on fossil fuels [1]. Among these fuels, crude oil plays a significant role in electricity generation [2–3]. However, the combustion of crude oil not only provides much-needed energy but also results in considerable carbon dioxide (CO_2) emissions [4–7]. In the case of power plants, their impact on the environment is almost always negative, ranging from direct environmental issues such as acid rain to indirect consequences like global warming and other related effects [8–12]. Therefore, understanding the scale of CO_2 emissions from industrial activities, is essential for regulating and implementing future mitigation strategies for burning fossil fuels, especially in developing countries [13].

Comparative research has underscored the benefits of optimizing fuel use, Moon et al. [14] found that energy production level significantly affects fuel efficiency, with outdated equipment leading to excessive fuel consumption and emissions in Asian thermal plant. Additionally, research by Zhao et al. and Su et al. [15–16]. Revealed that increasing energy output can improve thermal efficiency by reducing specific fuel consumption, suggesting that some plants may be underutilizing their potential at lower production levels.

Zhang et al. [17] used machine learning algorithms to predict fuel consumption and emissions in real time based on varying output levels in thermal power plants across East Asia. Their study found that optimized fuel consumption reduced CO_2 emissions by 18% while maintaining consistent energy output, particularly as production levels approached optimal efficiency ranges. Another digital study by Chen and Chen [18] employed exergy analysis to evaluate how different energy production levels affect the fuel consumption patterns in oil-fired plants, revealing that efficiency peaked when output was around 80% of the plant's maximum capacity, reducing specific fuel consumption significantly. A study by Liang et al. [19] explored the effects of production levels on thermal efficiency across multiple crude-oil-fired power plants in China, their findings indicated that thermal efficiency improved significantly as plants operated closer to their designed maximum output. By operating within a controlled output range, plants reduced specific fuel consumption by 20%, leading to a proportional reduction in CO_2 emissions [20–21]. Zhao et al. and Su et al. [15–16] work reinforces the idea that energy production levels are crucial in determining fuel efficiency and emissions.

Shrivastava et al.,[22] study found that Thermal efficiency increases when plants operate within 80-90% capacity, reducing fuel consumption by 15%. However, efficiency declines below optimal load levels, leading to excess fuel consumption and emissions. Marshall et al. [23] study found a 20% improvement in thermal efficiency between 85-95% of maximum capacity, highlighting the environmental and economic benefits of maximizing efficiency. López et al.'s [24] study found an 18% improvement in thermal efficiency at 90% capacity, recommending optimized load management strategies for older plants.

The present study aims to evaluate the carbon dioxide (CO_2) emissions and thermal efficiency of the Al-Mussaib Thermal Power Plant by analyzing the discrepancies between actual and ideal fuel consumption across various energy production levels. Using HYSYS software, the study quantifies the CO_2 emissions resulting from suboptimal crude oil consumption and identifies the load conditions that achieve optimal performance. By estimating the environmental and operational impacts of these discrepancies, the research seeks to provide insights into improving the plant's efficiency and reducing its carbon footprint, contributing to more sustainable energy production practices.

2. Theoretical Work

2.1. Power Plant Components

The Rankine cycle forms the basic principle of a steam power plant, where both heat addition and expansion processes are central to its operation. In a steam power plant, the boiler plays a key role, functioning as the heart of the system. As shown in Figure (1), the process begins with water entering the boiler, where it is pressurized and heated to produce steam at high temperature and pressure [25].

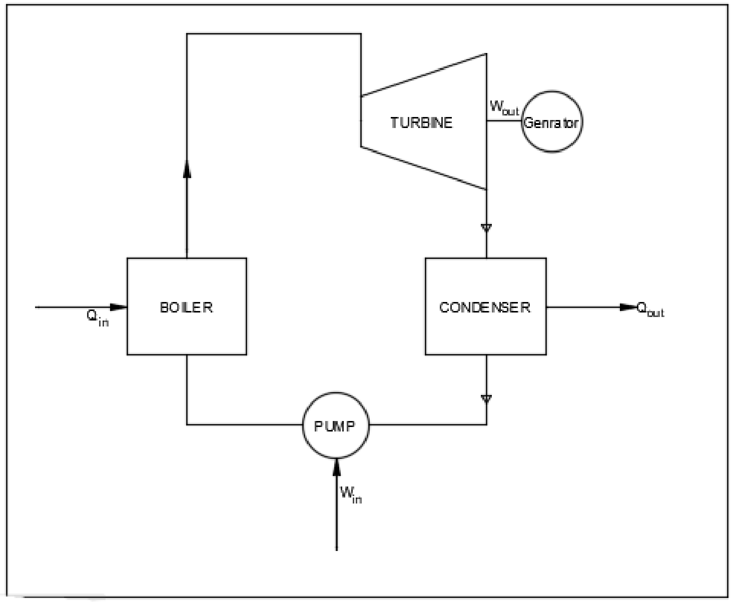

Figure (1): Simple Rankin Cycle diagram [25]

2.2. Field Data for Power Plant

The power complex consists of four 300 MW generating units, making it one of Iraq's highest-capacity active power plants. Units 1 and 2 sustained significant damage during the 1991 Gulf War, resulting in the suspension of their operations until they were recommissioned in 2000 and 2001. Despite the resumption of operations, the power output remains suboptimal, reaching no more than 70% of the rated capacity. Tables (1 & 2) present both actual and design field data for the boiler unit (Unit 1). Average daily operating data across varying periods were analyzed to achieve different load levels.

Table (1): Actual field data (Operating parameter of Unit 1) [26].

Active power (MW)	154.8	158.2	177	193	202	204
Main steam Temperature (°C)	532.6	537.9	538.85	538.19	536.9	540
Feed water Temperature Economizer Inlet T_{12}(°C)	136	136.7	136.8	130	145	145
Boiler side main steam pressure (bar)	144.3	144.4	145.9	140.3	154.7	154.9
* Fuel mass flow rate ($\frac{m^3}{h}$)	61.6	61.8	62.29	62.5	64	63.9
Eco INL FEED WATER PRES (bar)	139	138.6	150.4	145.9	152.3	152.6
FEED WATER FLOW (t/h)	600	610	653.7	646.6	661	672
Lower heating value LHV (kJ / kg)	42178	42178	42178	42178	42178	42178
**Cpa (kJ / kg k)	1.005	1.005	1.005	1.005	1.005	1.005
Density of crude oil $\frac{kg}{m^3}$	866.4	866.4	866.4	866.4	866.4	866.4

*Fuel (crude oil) mass flow rate, **Specific heat capacity of air

Table (2): Design field data of (Unit 1) [26].

Power MW	Fuel consumption (kg/s)
120	7.4
150	8.9
180	10.4
210	12.0
240	13.69
300	16.98

2.3. Simulation Using HYSYS

Aspen HYSYS (version 10), a comprehensive engineering software suite, is widely used for designing and simulating chemical and mechanical processes, particularly in the fuel, gas, and oil industries. HYSYS enables detailed modeling of complex processes; here, a steam boiler model was developed to simulate its function within the steam power cycle, as illustrated in Figure (2). This model includes critical components such as the feedwater inlet, combustion chamber, and steam generation section. Standard conditions assume water is heated by crude oil fuel, with air composition set at 21% oxygen and 79% nitrogen, and the Peng-Robinson (PR) fluid package selected for accurate hydrocarbon equilibrium predictions [27]. Fuel composition and crude oil properties are detailed in Table (3).

Table (3): Crude oil composition and properties [26]:

(a) Compositions of Crude oil

Component	Carbon	Hydrogen	Sulfur	Oxygen
Mass (%)	82.3	12.5	2	0.0

(b) Specifications of crude oil

Specification	Crude oil
Specific gravity at 15.56 °C	0.8572
Viscosity @ 21.11 °C	45 sec
Viscosity @ 37.78°C	39 sec*
Flash point**	138 °C
LHV***	42178 kJ / kg

*Sec typically refers to the time it takes for a specified volume of oil to flow through a viscometer.
**Flash point is the lowest temperature at which vapors of crude oil start to flash.
***Lower heating value LHV,

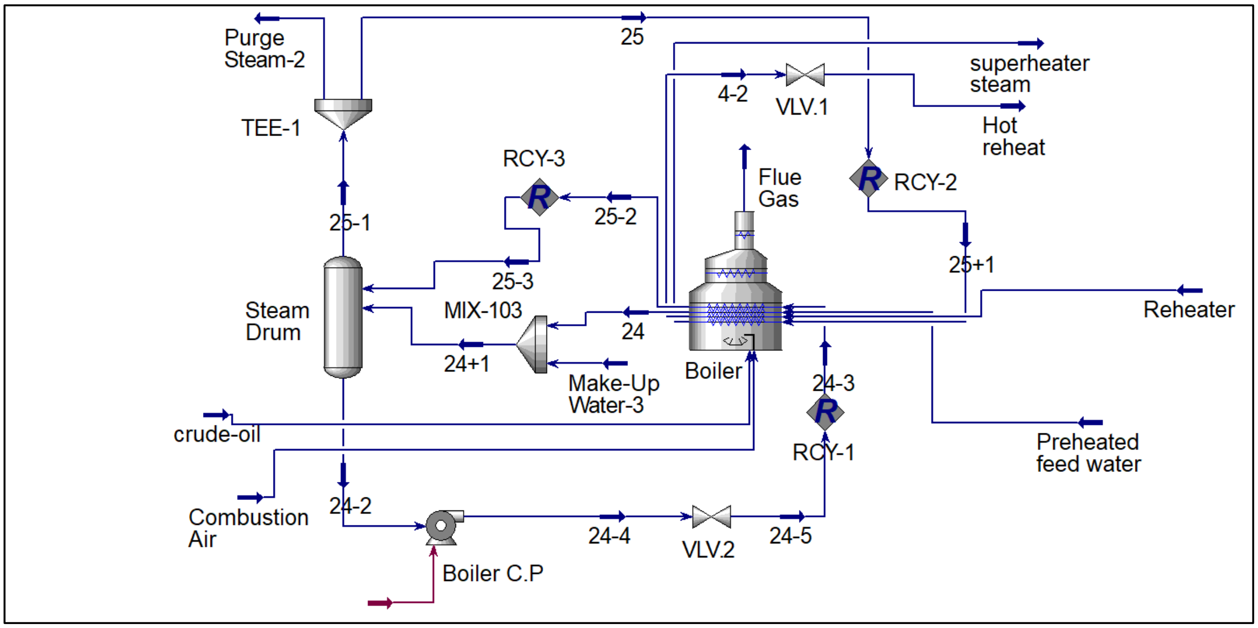

Figure (2): Aspen HYSYS model of the boiler flowsheet [28].

2.4. Theoretical Equations of Some Performance Parameters of Boiler Unit

The fuel mass flow rate (kg/s) is determined by Equation (1), (2) in kg/s units [29]:

$$\dot{v}_{\mathrm{f}} = (\textbf{fuel mass flow rate} \left(\frac{\mathrm{m^3}}{\mathrm{h}}\right) - 0.04022557) \times \mathrm{T_{12}})/3600 \qquad \textbf{(1)}$$

$$\dot{m}_{\mathrm{f}} = \mathrm{v_f} \times \rho_{\mathrm{f}} \qquad \textbf{(2)}$$

Where $\dot{v}_f$: Fuel volume flow rate $(\frac{m^3}{s})$, ρ_f: Density of crude oil $(\frac{kg}{m^3})$, T_{12}: Feed water Temperature Economizer Inlet (˚C)

The overall thermal efficiency η_{th} is calculated using Equation (3) [29]:

$$\eta_{th} = \frac{Power}{\dot{m}_f \times (LHV)} \qquad \textbf{(3)}$$

Where $\dot{m}_f$: Actual Fuel mass flow rate (kg/s), LHV: Lower heating value of the fuel (kJ/kg).

The specific fuel consumption (SFC), expressed in kg/kWh, is calculated using Equation (4) [29]:

$$SFC = \frac{\dot{m}_f \times 3600}{Power} \qquad \textbf{(4)}$$

The heat rate (HR) represents the amount of heat consumed to generate one unit of electrical energy. It can be calculated using Equation (5) and is expressed in kJ/kWh:

$$HR = \frac{3600}{\eta_{th}} \qquad \textbf{(5)}$$

3. Results and Discussion

Thermal power plants in Iraq, like Musayyib, are indispensable for ensuring energy stability across the national grid. As such, they aim to maintain consistent electricity generation despite challenges. The study centers on simulating boiler performance, as depicted in Figure (2), using the Aspen HYSYS program. This simulation allows for a detailed analysis of the combustion process and heat transfer mechanisms within the boiler. By incorporating the physical and chemical properties of crude oil.

Figure (3) shows in this thermal power plant, the actual fuel consumption was significantly higher than the design specifications. To generate 155 MW, the design fuel consumption was set at 9.2 kg/s. However, the actual consumption increased to 13.4 kg/s, representing an excess of 4.2 kg/s above the design level a 45.7% increase in fuel usage for the same output.

When the power output was raised to 205 MW, the actual fuel consumption rose to 14 kg/s, compared to the design fuel consumption of 11.4 kg/s. surpassing the design flow rate by 2.2 kg/s. The analysis reveals that the fuel consumed in the thermal power plant aligns more closely with the design specifications when energy production is at 70% of the design capacity. This indicates that as the plant operates closer to the design load, the gap between actual and design fuel consumption narrows, enhancing overall efficiency.

Conversely, at lower energy production levels, the difference between actual and design fuel consumption increases significantly. This increase can primarily be attributed to issues related to the boiler's performance. When the steam temperature reaching the boiler is lower than optimal, it diminishes the efficiency of the steam generation process. This comparison highlights that while increasing fuel consumption improved power output to some extent, the plant still consumed more fuel than originally intended, pointing to potential areas for optimization in fuel usage.

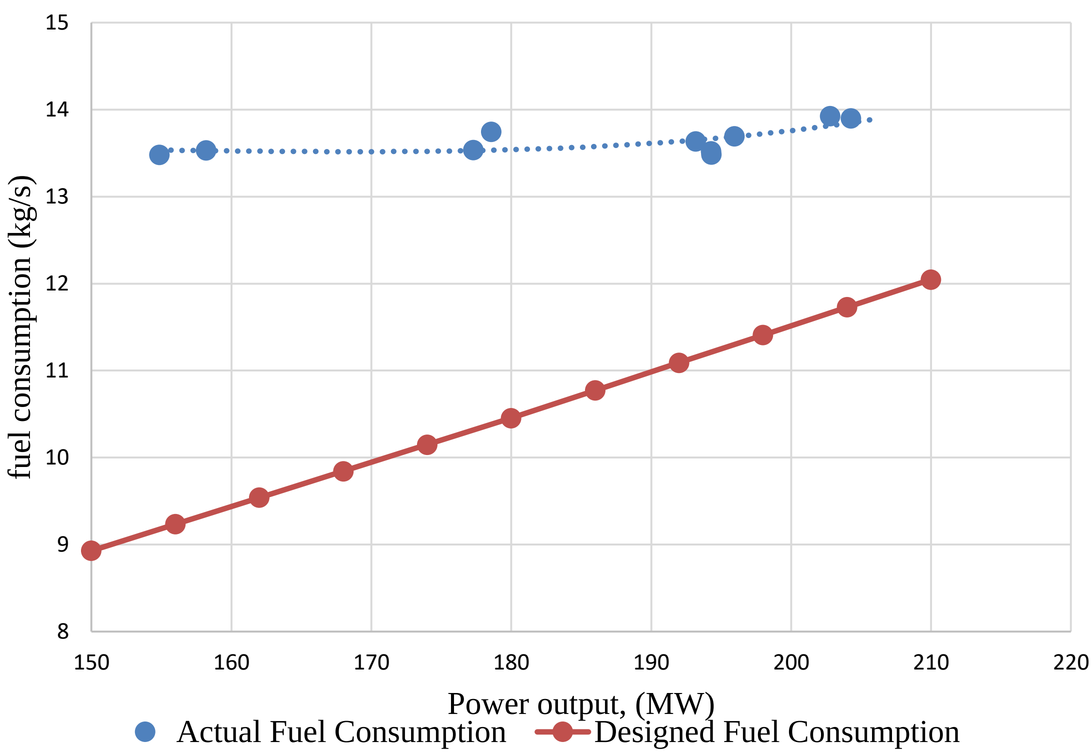

Figure (3): Comparison of Actual vs. Designed Fuel Consumption.

The relationship between the thermal efficiency of a steam power plant and its carbon dioxide (CO_2) emissions is inversely proportional, as demonstrated in Figure (4). These results, obtained using Aspen HYSYS software, show that the lowest thermal efficiency, 27%, emitted 0.95 kg/kWh of CO_2. This relatively low thermal efficiency indicates that a significant portion of the energy in the fuel is lost as waste heat rather than being converted into useful electrical energy. In contrast, the station with the highest thermal efficiency, 34.8%, emitted 0.2 kg/kWh less CO_2 compared to the lowest efficiency.

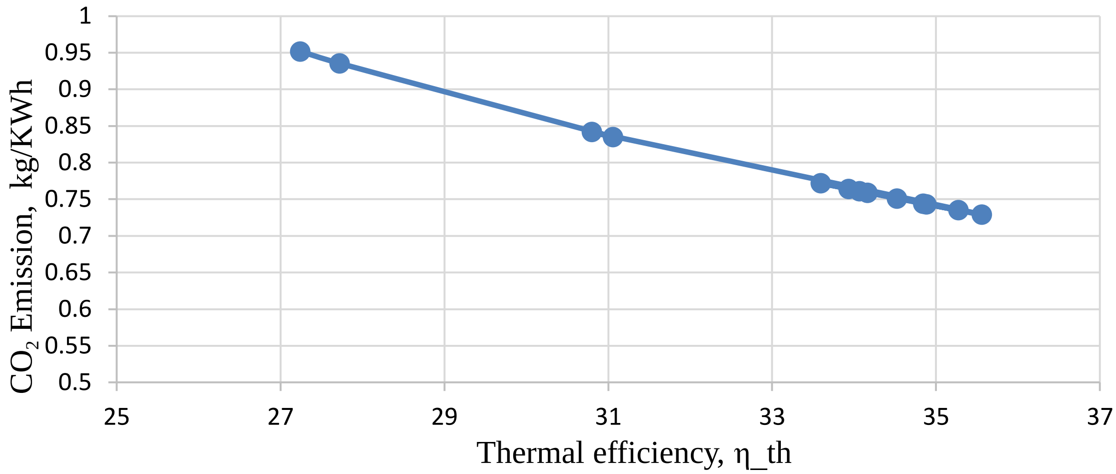

Figure (4): Relation between thermal efficiency and CO_2 emission.

Using Aspen HYSYS, CO_2 emissions were determined by simulating the combustion process of crude oil, utilizing its specific properties and chemical composition. This study focused on calculating the specific carbon dioxide (CO_2) emissions generated during electricity production at the Al-Mussaib Thermal Power Plant in Iraq, based on real operating data. The analysis revealed that a specific fuel consumption (SFC) of 0.24 kg/kWh produced CO_2 emissions of 0.75 kg/kWh, while an increase in SFC to 0.31 kg/kWh resulted in higher CO_2 emissions of 0.95 kg/kWh, as depicted in Figure (5). The results demonstrate that increasing thermal efficiency reduces CO_2 emissions per unit of electricity generated, underscoring a direct relationship between fuel efficiency and emissions. This highlights the critical need to enhance thermal efficiency for reducing environmental impacts and ensuring sustainable plant operations.

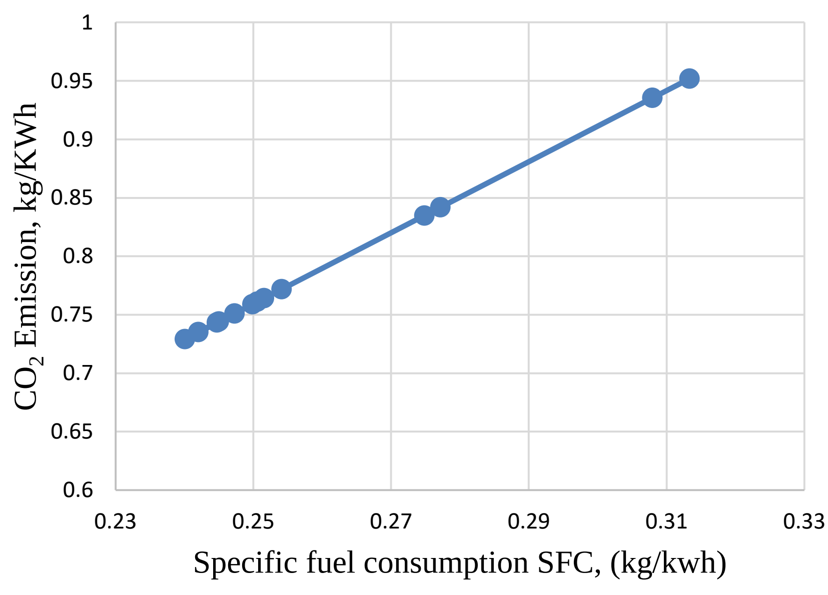

Figure (5): SFC with CO_2 Emission.

Similarly, Lee et al. found that outdated machinery in Asian factories contributed to excessive fuel usage and increased CO_2 emissions. This issue is also evident at Al-Mussaib, where fuel consumption exceeds recommended levels.

The Figure (6) compares between designed and actual thermal efficiency across power output levels, for instance, at a power output of 155 MW, the designed efficiency is around 41.3%, while the actual efficiency is lower of 27%. This discrepancy suggests potential system inefficiencies, such as heat loss or mechanical inefficiencies.

Regular maintenance and optimization of thermal systems can bridge this gap, with improvements in insulation, heat recovery systems, and advanced control technologies enhancing actual thermal efficiency.

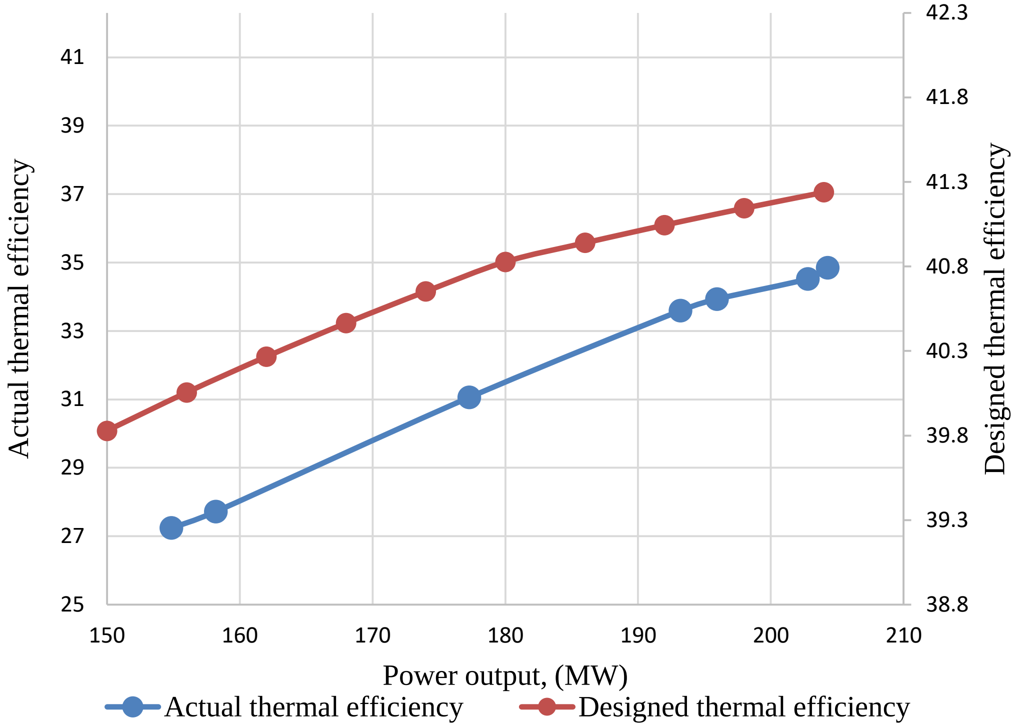

Figure (6): Compares between designed and actual thermal efficiency across power output levels.

Figure (7) illustrates the effect of the power output levels on the heat rate for crude oil of fuel. As the plant's energy output rose from 155 MW to 205 MW, the temperature rate of crude oil dropped a 21.8% decrease. The likely causes include better heat transfer efficiency and reduced energy losses at higher outputs, as power plants typically operate more efficiently when closer to their design capacity.

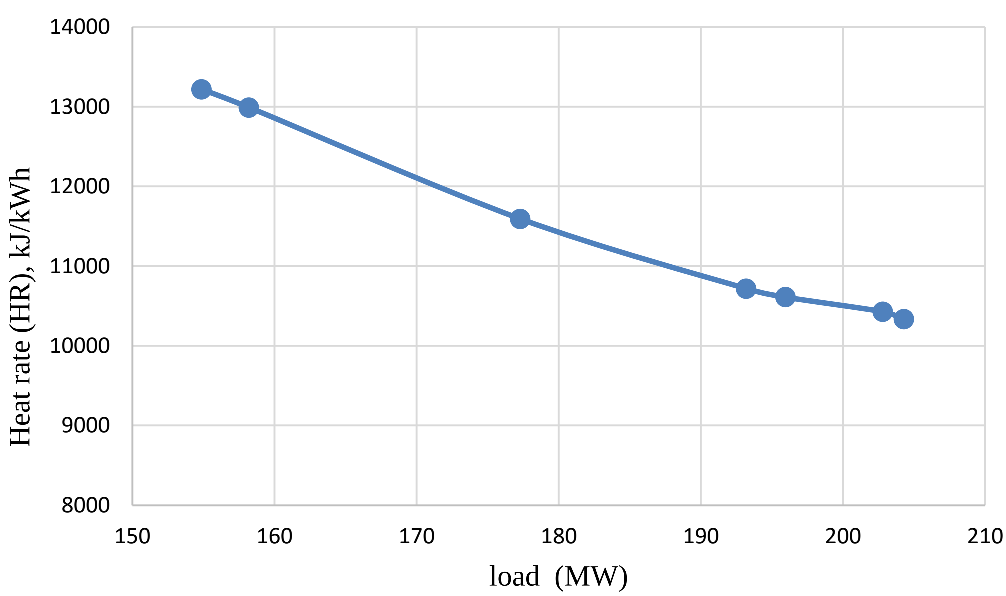

Figure (7): Impact of power output levels on the heat rate.

4. Conclusions

The relationship between fuel consumption and CO_2 emissions at the Al-Mussaib Thermal Power Plant is a key focus of this research, highlighting the importance of efficient fuel usage to reduce environmental impact. By utilizing HYSYS software, the study quantifies CO_2 emissions resulting from inefficient crude oil consumption and identifies load conditions that optimize performance, addressing notable shortcomings at the facility. With 13.4 kg/s of crude oil burned to produce 155 MW, resulting in 13.9 kg/s of CO_2 emissions. In contrast, optimal operation requires only 33242 kg/h of fuel, similar inefficiencies were identified at a high capacity of 205 MW, largely due to outdated equipment, low boiler efficiency, and poor maintenance. The design of a thermal system, with a power output of 155 MW, shows a 27% actual efficiency, suggesting potential system inefficiencies. Regular maintenance and optimization can improve efficiency. Operating at this 70% load, reduces unnecessary fuel use, optimizing energy conversion efficiency and lowering emissions. This balance supports sustainable and cost-effective power generation. As production increases, the gap between actual and design fuel consumption decreases from 4.2 kg/s to 2.2 kg/s, indicating improved efficiency at higher operational loads.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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