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Assessing Combustion Air Demand and Environmental Impacts of Fuel Choices in Industrial Steam Generation

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ABSTRACT- This study investigates the impact of various fuels including Natural Gas, Diesel, Coal, and Biomass on the air requirements for combustion as well as the environmental impacts within the context of steam production in industries, particularly Bangladesh. This stems from the ongoing fossil fuel crises and the need for an environmentally friendly effective energy solution. Many Bangladeshi factories suffer from poor ventilation and operate with malfunctioning boilers which leads to fuel wastage while exacerbating emissions. To address the problem, the study integrates stoichiometric combustion analysis, thermodynamic calculations, and environmental impact assessments to focus on fuel performance. A case study of a 5000 kg/hr steam generation system is analyzed. Among the fuels analyzed, Natural gas emerges as the most efficient and cleanest, requiring only 317.29 kg/hr and emitting 866.37 kg/hr of CO_2 with no SO_2 emissions. Biomass, although renewable, requires the highest quantity of fuel while contributing a moderate level of CO_2 emissions. The existing coal and diesel variants are higher contributors to airborne pollutants including sulfur dioxide. The study conclusively demonstrates how significant air-to-fuel ratios are and fuel selection for industrial efficiency.

KEYWORDS: Steam Generation, Emission, Combustion, Stoichiometry, Biomass.

I. INTRODUCTION

Bangladesh is scuffling with a growing fossil fuel extremity, driven by shrinking domestic gas reserves and a rising reliance on imported energy sources [1]. As diligence — especially in fabrics and manufacturing — continue to expand, the demand for brume in boiler systems remains a core functional need [2]. Meeting this demand efficiently is vital, not just to keep energy costs under control, but also to reduce pressure on the country's limited fossil fuel inventories [3]. Choosing the right energy, still, is not purely a matter of economics — it has major environmental counteraccusations as well. Inefficient combustion does not just waste energy; it also results in advanced emigrations and worsens air pollution. In numerous manufactories across Bangladesh, boiler apartments are confined, with poor ventilation and confined tailwind. These conditions hamper proper combustion and pose safety pitfalls [3]. When air rotation is shy, deficient combustion becomes more likely — releasing dangerous feasts like carbon monoxide (CO), sulfur oxides (SO_x), and nitrogen oxides (NO_x). These adulterants not only harm the terrain but also produce dangerous working conditions. likewise, if energy types are chosen without considering how important combustion air they bear, boiler systems can come hamstrung, wasting energy and adding emigrations [4]. That's why a careful comparison of different energies — looking nearly at their air conditions and emigration biographies is essential for perfecting both boiler performance and environmental safety. Figure 1 illustrates the steam generation process that underpins these challenges.

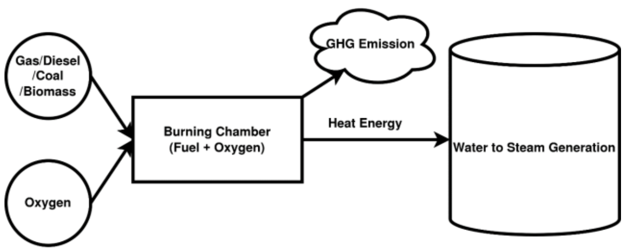

Figure 1: Industrial steam generation process by combusting fuels

In this situation, this study aims to answer the following key research questions (RQ):
RQ1. How do different fuels (Natural Gas, Diesel, Coal, Biomass) compare in terms of combustion air requirements for steam generation?
RQ2. What are the environmental impacts of these fuel choices in terms of emissions and efficiency?
RQ3. How can optimizing air-to-fuel ratios enhance boiler performance and reduce hazardous emissions?
To address these questions, the study sets the following research objectives (RO):
RO1. To quantify and compare the combustion air demand for various fuels used in boilers.
RO2. To analyze the environmental impact of fuel based on emissions and energy efficiency.

RO3. To provide recommendations for optimizing fuel selection in congested boiler rooms with limited ventilation.

This research employs a comparative analytical approach, integrating theoretical combustion calculations.

The study begins by gathering data on fuel properties and combustion geste from boiler primers, published exploration, and thermodynamic reference tables. Using this information, stoichiometric combustion computations are carried out to estimate the quantum of air demanded for complete combustion of each energy. To estimate environmental impact, emigrations of CO_2, CO, and sulfur oxides (SO_x) are calculated grounded on the energies' chemical makeup and anticipated effectiveness. The analysis also compares different energies by importing their effectiveness, air conditions, and emigration situations to identify which option stylish suits the requirements of Bangladesh's artificial sector.

This approach is chosen because it blends theoretical modeling with real- world data, allowing for meaningful perceptivity without the complexity or cost of large- scale trials. By combining these styles, the study offers a practical yet rigorous way to estimate combustion effectiveness and environmental consequences.

The results aim to support a range of stakeholders — from artificial decision- makers and boiler drivers to environmental controllers — by offering clear guidance on energy choices that balance performance with sustainability. Reducing energy use not only cuts costs but also helps produce safer working surroundings. Also, fine-tuning the air- to- energy rate can significantly ameliorate boiler operation while lowering dangerous emigrations. Beyond its specialized benefactions, the exploration is anticipated to inform unborn programs on energy selection and air quality control in artificial settings, aligning with Bangladesh's broader vision for cleaner and more effective energy use.

II. METHODOLOGY

A. Research design and theories

This study employs a comparative analytical approach to evaluate the combustion air demand and environmental impacts of different fuels used in industrial steam generation. The exploration is grounded on stoichiometric combustion principles, which determine the theoretical air-to- energy rate needed for complete combustion. The study also integrates thermodynamic and emigration analysis, assessing how different energies impact boiler effectiveness and emigrations.

The key theoretical foundations of this study include:

Stoichiometric Combustion Theory: The calculation of the exact amount of oxygen required to fully combust a given fuel without excess air [5].

Thermodynamics of Steam Generation: The relationship between fuel energy content, boiler efficiency, and steam generation capacity [6].

Environmental Impact Assessment: Evaluating the emissions of CO_2, CO, and SO_x based on fuel composition and combustion efficiency [7].

By applying these theories, the study aims to provide an optimized fuel selection strategy that balances efficiency, air demand, and environmental impact in industrial settings.

B. Data collection

The dataset includes parameters such as:

Boiler operating conditions (efficiency, steam pressure, inlet/outlet temperatures).

Fuel properties (Lower Heating Value (LHV), Higher Heating Value (HHV), carbon content, and fuel mass flow rate).

Combustion air demand and pollutant emissions for each fuel type.

Considerations for this case study were-

Boiler feed water temperature, T_{in}= 20^0C (Room temperature)

Steam out temperature, T_s= 184^0C (Saturated steam temperature at 10 bar pressure)

Burner Efficiency, η= 85%

Steam generation rate of boiler, $\dot{m}$= 5000 kg/hr

Properties of different fuel can be found in Table 1.

Table 1: Different fuel properties

Fuel name	Chemical composition	Calorific value
Natural Gas	CH_4 (95%), C_2H_6 (3%) C_3H_8 (1%), N_2 (1%) [8] [9]	50 MJ/kg (LHV) [10]
Diesel	C (86%), H (13.75%), S (0.15%), Ash (0.1%) [11]	42.6 MJ/Kg (LHV) [11]
Coal (Barapukuria)	C (83%), H (5.1%), N (1.7%), S (0.77%), O (9.4%), Ash (13.4%) [12]	34.63 MJ/kg (HHV) [13]
Biomass (Husk-rice)	C (38.5%), H (5.7%), N (0.5%), O (39.8%), Ash (15.5%) [14]	24.45 MJ/kg (HHV) [14]

C. Calculations

In this study, it is assumed that no N_2 combustion occurs due to burner temperatures being below 1000°C. It is also assumed that, for complete combustion, 10% excess air is required for fluid fuels (natural gas and diesel), while 20% excess air is needed for solid fuels (coal and biomass).

For natural gas, the total fuel required for generating 5000 kg/hr of steam is 317.29 kg/hr (using values from Table 1).

For complete combustion, each fuel component reacts with oxygen (O_2) as follows:

Methane Combustion-

$CH_4+2O_2 \rightarrow CO_2+2H_2O$

Mass of methane required: 301.43 kg/hr; Molar mass of CH_4 = 16 g/mol; Oxygen required per mole of CH_4 = 2 moles; Total oxygen required for CH_4 combustion: 1205.72 kg/hr.

Ethane Combustion-

$C_2H_6+3.5O_2 \rightarrow 2CO_2+3H_2O$

Mass of ethane required: 9.52 kg/hr; Molar mass of C_2H_6 = 30 g/mol; Oxygen required per mole of C_2H_6 = 3.5 moles; Total oxygen required for C_2H_6 combustion: 10.15 kg/hr.

Propane Combustion-
$C_3H_8+5O_2 \rightarrow 3CO_2+4H_2O$
Mass of propane required: 3.17 kg/hr; Molar mass of C_3H_8 = 44 g/mol; Oxygen required per mole of C_3H_8 = 5 moles; Total oxygen required for C_3H_8 combustion: 2.31 kg/hr.

Total Oxygen and Air Requirement-
Total oxygen required: 1218.18 kg/hr; Total air required: 5264.38 kg/hr; Optimum air required (including excess air for complete combustion): 5790.82 kg/hr.
Methane CO_2 Production 828.93 kg/hr; Ethane CO_2 Production 27.92 kg/hr; Propane CO_2 Production 9.52 kg/hr.
Total CO_2 Emissions 866.37 kg/hr.
Since natural gas is composed of hydrocarbons with minimal sulphur content, there is no sulphur dioxide (SO_2) emission in this combustion process.
For diesel, the total fuel required for combustion is 372.41 kg/hr (using values from Table 1).
For complete combustion, each fuel component reacts with oxygen (O_2) as follows:

Carbon Combustion-
$C+O_2 \rightarrow CO_2$
Mass of carbon in diesel: 320.27 kg/hr; Molar mass of carbon (C) = 12 g/mol; Oxygen required per mole of C = 1 mole; Total oxygen required for C combustion: 854.06 kg/hr.

Hydrogen Combustion-
$H_2+0.5O_2 \rightarrow H_2O$
Mass of hydrogen in diesel: 51.22 kg/hr; Molar mass of H_2 = 2 g/mol; Oxygen required per mole of H_2 = 0.5 moles; Total oxygen required for H_2 combustion: 409.65 kg/hr.

Sulfur Combustion-
$S+O_2 \rightarrow SO_2$
Mass of sulfur in diesel: 0.56 kg/hr (0.15% of total fuel); Molar mass of sulfur (S) = 32 g/mol; Oxygen required per mole of S = 1 mole; Total oxygen required for S combustion: 0.56 kg/hr.

Total Oxygen and Air Requirement-
Total oxygen required: 1264.27 kg/hr; Total air required: 5463.58 kg/hr; Optimum air required (including excess air for complete combustion): 6009.94 kg/hr.

CO_2 emission: 1174.34 kg/hr; SO_2 emission: 1.12 kg/hr.
For Coal, the total fuel required for combustion is 475.31 kg/hr (using values from Table 1).
For complete combustion, each fuel component reacts with oxygen (O_2) as follows:

Carbon Combustion-
$C+O_2 \rightarrow CO_2$
Mass of carbon in coal: 394.51 kg/hr; Molar mass of carbon (C) = 12 g/mol; Oxygen required per mole of C = 1 mole; Total oxygen required for C combustion: 1052.03 kg/hr.

Hydrogen Combustion-
$H_2+0.5O_2 \rightarrow H_2O$
Mass of hydrogen in coal: 24.44 kg/hr; Molar mass of H_2 = 2 g/mol; Oxygen required per mole of H_2 = 0.5 moles; Total oxygen required for H_2 combustion: 193.93 kg/hr.

Sulphur Combustion-
$S+O_2 \rightarrow SO_2$
Mass of sulfur in coal: 3.66 kg/hr; Molar mass of sulfur (S) = 32 g/mol; Oxygen required per mole of S = 1 mole; Total oxygen required for S combustion: 3.66 kg/hr.

Total Oxygen and Air Requirement-
Total oxygen required: 1204.94 kg/hr; Total air required: 5207.17 kg/hr; Optimum air required (including excess air for complete combustion): 6248.60 kg/hr.
CO_2 emission: 1446.54 kg/hr; SO_2 emission: 7.32 kg/hr.
For biomass, the total fuel required for combustion is 683.90 kg/hr (using values from Table 1).
For complete combustion, each fuel component reacts with oxygen (O_2) as follows:

Carbon Combustion-
$C+O_2 \rightarrow CO_2$
Mass of carbon in biomass: 263.70 kg/hr; Molar mass of carbon (C) = 12 g/mol; Oxygen required per mole of C = 1 mole; Total oxygen required for C combustion: 702.14 kg/hr.

Hydrogen Combustion-
$H_2+0.5O_2 \rightarrow H_2O$
Mass of hydrogen in biomass: 38.99 kg/hr; Molar mass of H_2 = 2 g/mol; Oxygen required per mole of H_2 = 0.5 moles; Total oxygen required for H_2 combustion: 311.86 kg/hr.

Total Oxygen and Air Requirement-
Total oxygen required: 741.81 kg/hr; Existing oxygen in biomass: 272.19 kg/hr; Additional oxygen required: 469.61 kg/hr; Total air required: 3205.74 kg/hr; Optimum air required (including excess air for complete combustion): 3846.89 kg/hr.
CO_2 emission: 965.45 kg/hr.
Since biomass (rice husk) has no sulphur content, there is no sulphur dioxide (SO_2) emission in this combustion process.

III. RESULTS AND DISCUSSION

Results of this study can be found in Table 2.

Table 2: Calculated results of this study for 5000 kg/hr steam generation

Fuel name	Total Fuel Required (kg/hr)	Total Oxygen Demand (kg/hr)	Total Air Requirement (kg/hr)	Total CO_2 Emissions (kg/hr)	SO_2 Emissions (kg/hr)
Natural Gas	317.29	1218.18	5264.38	866.37	0
Diesel	372.41	1264.27	6009.94	1174.34	1.12
Coal	475.31	1204.94	6248.60	1446.54	7.32
Biomass	683.90	741.81	3846.89	965.45	0

Figure 2 shows the difference in fuel required to generate 5000 kg of steam per hour. The fuel requirement increases from Natural Gas to Biomass, which is consistent with the

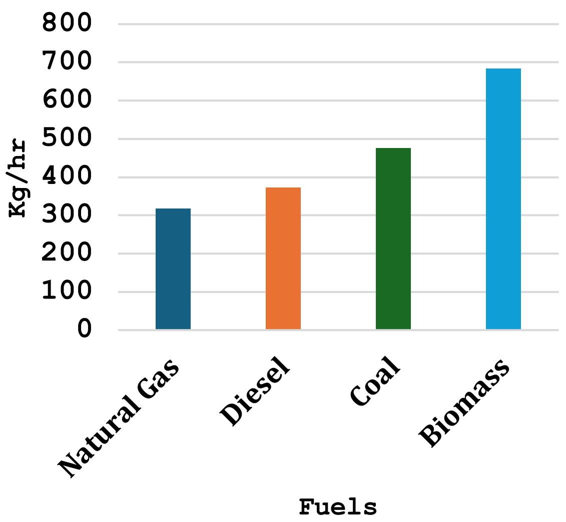

Figure 2: Fuel required per hour

energy density of these fuels. Natural gas has the highest energy density, requiring the least amount of fuel, while biomass has the lowest energy density, requiring the most. Figure 3 shows the difference in air requirements per hour in the boiler room for complete combustion of different types of fuel in this case. Oxygen demand is generally proportional to the carbon and hydrogen content in the fuel. Diesel and Natural Gas have higher oxygen demands due to their higher hydrogen content. Biomass has a lower oxygen demand, possibly due to its lower carbon content and higher moisture content. Air requirement is higher for fuels with higher oxygen demand. However, Biomass has a lower air requirement despite its lower oxygen demand, which could be due to its lower combustion efficiency or higher moisture content.

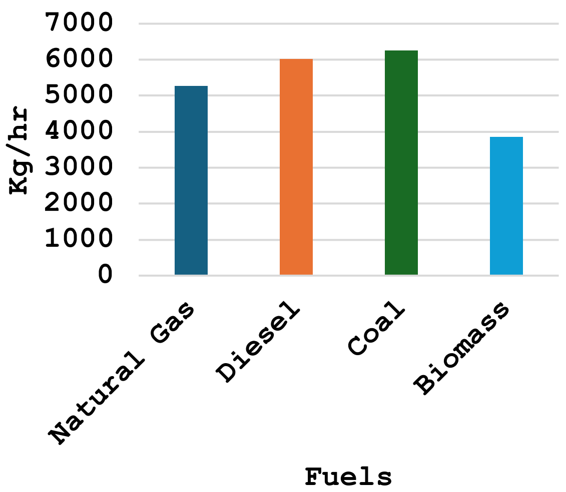

Figure 3: Air requirement in boiler room for complete combustion

Figure 4 compares CO_2 emissions per hour for different types of fuels. CO_2 emissions are generally proportional to the carbon content of the fuel. Coal has the highest CO_2 emissions due to its high carbon content, while Natural Gas has the lowest due to its higher hydrogen-to-carbon ratio.

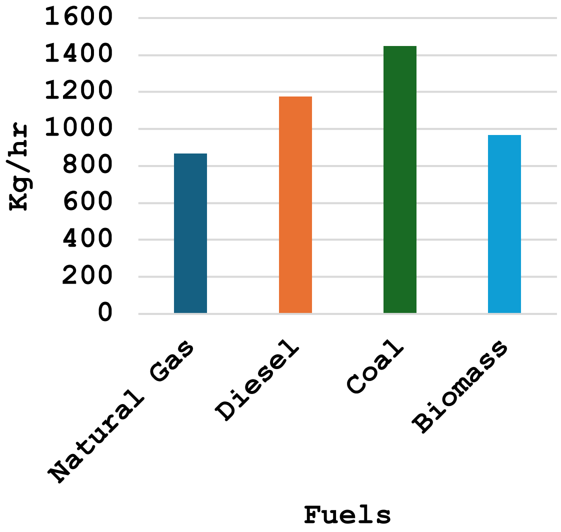

Figure 4: CO_2 emissions per hour for different types of fuels

Figure 5 describes the comparison of SO_2 emissions per hour for different types of fuels. Natural Gas and Biomass have negligible sulfur content, resulting in zero SO_2 emissions. Diesel and Coal have higher sulfur content, leading to measurable SO_2 emissions, with Coal having the highest due to its significant sulfur content.

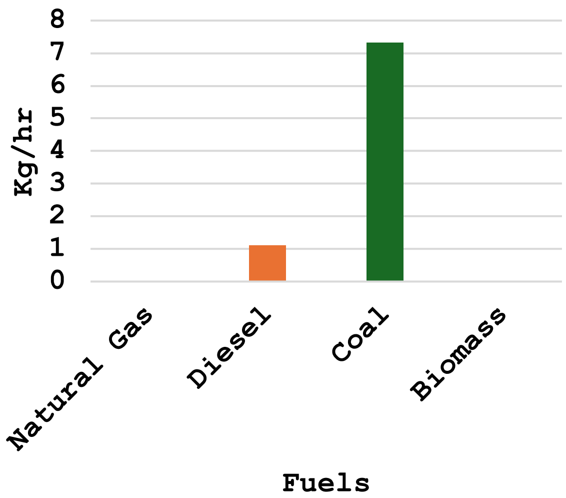

Figure 5: SO_2 emissions comparisons

IV. MANAGERIAL IMPLICATIONS

The findings of this research hold significant implications for the manner in which Bangladeshi industries make fuel choices, boiler utilization, safety, and sustainability—particularly within Industry 4.0. With increasing energy needs and environmental concerns, the research can inform policymakers to make decisions towards better, cleaner, and smarter practices.

Of all the fuels considered, natural gas is the most efficient and the least contaminating. It only needs 317.29 kg/hr to generate the desired output of steam and has the lowest CO_2 emission (866.37 kg/hr), with zero SO_2 emissions.

Where infrastructure and supply are within reach, it must be the primary option for industrial boiler use. Still, considering Bangladesh's current fuel shortage, biomass provides the renewable solution. Although it has moderate CO_2 emissions (965.45 kg/hr) but no SO_2 emissions, it requires the maximum fuel input (683.9 kg/hr), which might be costly to operate. Nevertheless, if harvested responsibly and utilized efficiently, biomass is a great prospect for the utilization of sustainable energy.

One of the most important lessons is the need for proper air supply for complete combustion. Natural gas and diesel need more volume of air (more than 5000 kg/hr) because of their greater oxygen requirement. Coal and biomass need lesser, though still require precise air regulation to prevent incomplete combustion, resulting in dangerous emissions and safety issues. Ventilation systems strong enough to provide the required air to the selected fuel must be installed in boiler rooms. In the absence of sufficient airflow, combustion efficiency is lost, emissions increase, and working hazards multiply.

Environmentally, both natural gas and biomass have obvious advantages, especially in respect to minimal SO_2 emissions. Stepping towards these fuels aids national and global sustainability initiatives and converges with new regulatory requirements. Biomass, in turn, holds promise in the industrial environment as part of a general bioenergy initiative within the global energy transition.

All that being said, both of the fuels carry risks with them that must be managed. Natural gas is extremely flammable and thus has to have appropriate storage, handling, and leak detection mechanisms in place. Biomass burning can produce particulate and ash, and thus effective cleaning and filtration systems must be used to safeguard workers and equipment.

Lastly, combining Industry 4.0 technologies like IoT sensors, real-time monitoring, and analytics powered by AI can further optimize boiler performance [15]. These technologies can monitor continuously fuel consumption, air intake, and emissions, enabling operators to adjust combustion processes and cut costs. Furthermore, automated emissions reporting can assist companies in complying with environmental legislation and achieving sustainability goals. To adopt digital solutions can not only make boiler operations smarter and safer, but align them with the transition to cleaner energy systems as well.

V. CONCLUSION

This study investigation specifically addressed its objectives by measuring the air needed for combustion processes, assessing the environmental impact of various fuels, and providing recommendations related to steam fuel selection for industrial use. Out of the alternatives analyzed, natural gas was identified as the most efficient and least damaging to the environment, with biomass noted as a less efficient but promising renewable option [16]. The findings emphasize the importance of the choice of fuel as well as sufficient air supply in lowering emissions while enhancing boiler operation.

Even so, there are some constraints with the research. Its results stem from theoretical frameworks with simplified assumptions that may not capture the full range of complexities faced in actual industrial environments. To expand on this research, subsequent studies should direct their attention toward experimental validation, the use of novel combustion automation systems, and the socio-economic aspects of transitioning to cleaner fuels within Bangladesh's industrial landscape.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Majumder, S., Payel, S. B., Siraj, M. T., Rahaman, M., and Chowdhury, M. K. H., “A Comparative Analysis of Bangladesh's Energy Emissions: Implications for Carbon Neutrality and Sustainability,” in *6th Industrial Engineering and Operations Management Bangladesh Conference*, Dhaka, Bangladesh, 2023. Available from: https://tinyurl.com/5b2j5p5u
2. Siraj, M. T., Hasan, M. M., Ahmed, A. F., Faruk, F. B., Ahmed, M. F., Chowdhury, M. K. H., et al., “Steam Boilers in Ready-Made Garments Industry in Bangladesh: Existing Scenario and Scope for Development,” *Journal of Engineering Science*, vol. 14, no. 2, pp. 89–105, 2023.
3. Siraj, M. T., Debnath, B., Kumar, A., Bari, A. M., Samadhiya, A., and Payel, S. B., “Evaluating barriers to sustainable boiler operation in the apparel manufacturing industry: Implications for mitigating operational hazards in the emerging economies,” *PLOS One*, vol. 18, no. 4, e0284423, 2023. Available from: https://doi.org/10.1371/journal.pone.0284423
4. Siraj, M. T., Hasan, M. M., Ahmed, A. F., Faruk, F. B., Ahmed, M. F., Chowdhury, M. K. H., et al., “Steam Boilers in Ready-Made Garments Industry in Bangladesh: Existing Scenario and Scope for Development,” *Journal of Engineering Science*, vol. 14, no. 2, pp. 89–105, 2023.
5. Mishra, D. P., *Fundamentals of Combustion*, PHI Learning Pvt. Ltd., 2007. Available from: https://tinyurl.com/4wea3xsp
6. Hamayun, M. H., Hussain, M., Shafiq, I., Ahmed, A., and Park, Y. K., “Investigation of the thermodynamic performance of an existing steam power plant via energy and exergy analyses to restrain the environmental repercussions: A simulation study,” *Environmental Engineering Research*, vol. 27, no. 1, 2022. Available from: https://doi.org/10.4491/eer.2020.683
7. Li, C., Gillum, C., Toupin, K., Park, Y. H., and Donaldson, B., “Environmental performance assessment of utility boiler energy conversion systems,” *Energy Conversion and Management*, vol. 120, pp. 135–143, 2016. Available from: https://doi.org/10.1016/j.enconman.2016.04.099
8. Heywood, J., *Internal Combustion Engine Fundamentals*, 2nd ed., 2018. Available from: https://tinyurl.com/5n74db24
9. Speight, J. G., *The Chemistry and Technology of Petroleum*, CRC Press, 2006. Available from: https://doi.org/10.1201/9781420008388
10. Noor, M. M., Wandel, A. P., and Yusaf, T., “The development of MILD combustion open burner experimental setup,” in *Proc. 2nd Int. Conf. on Mechanical Engineering Research (ICMER 2013)*, University of Southern Queensland, Jan. 2013. Available from: https://tinyurl.com/4fvc8szu
11. Huth, M., and Heilos, A., “Fuel flexibility in gas turbine systems: impact on burner design and performance,” in *Modern Gas Turbine Systems*, pp. 635–684, Woodhead Publishing, 2013. Available from: https://doi.org/10.1533/9780857096067.3.635

12. Alam, F., “Energy, Exergy and Environmental Impact Analyses of Barapukuria Coal Based Thermal Power Plant,” 2013. Available from: http://lib.buet.ac.bd:8080/xmlui/handle/123456789/89
13. Glassman, I., Yetter, R. A., and Glumac, N. G., *Combustion*, Academic Press, 2014. Available from: https://tinyurl.com/yzsm57dm
14. Basu, P., *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory*, Academic Press, 2018. Available from: https://tinyurl.com/5x4kyfhj
15. Payel, S. B., Ahmed, S. F., Taseen, N., Siraj, M. T., and Shahadat, M. R. B., “Challenges and opportunities for achieving operational sustainability of boilers in the context of Industry 4.0,” *International Journal of Industrial Management*, vol. 17, no. 3, pp. 138–151, 2023. Available from: https://doi.org/10.15282/ijim.17.3.2023.9062
16. Zaman, M. E., Kayum, M. A., Chowdhury, M. K. H., and Barai, T., “U.S. renewable energy capacity in 2024: Sustainable transition and global competitiveness,” *World Journal of Advanced Research and Reviews*, vol. 26, no. 3, pp. 2351–2360, 2025. Available from: https://doi.org/10.30574/wjarr.2025.26.3.2449