Thermal Science and Engineering 2024, 7(3), 9125.
https://doi.org/10.24294/tse.v7i3.9125

Article

Thermodynamic evaluation of an IGCC power plant utilizing allothermal gasification

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CITATION

Choudhary NK, Ghosh S, Karmakar S. Thermodynamic evaluation of an IGCC power plant utilizing allothermal gasification. Thermal Science and Engineering. 2024; 7(3): 9125.
https://doi.org/10.24294/tse.v7i3.9125

ARTICLE INFO

Received: 6 July 2024
Accepted: 25 August 2024
Available online: 18 September 2024

Abstract: The present work conducts a comprehensive thermodynamic analysis of a 150 MW_e Integrated Gasification Combined Cycle (IGCC) using Indian coal as the fuel source. The plant layout is modelled and simulated using the "Cycle-Tempo" software. In this study, an innovative approach is employed where the gasifier's bed material is heated by circulating hot water through pipes submerged within the bed. The analysis reveals that increasing the external heat supplied to the gasifier enhances the hydrogen (H_2) content in the syngas, improving both its heating value and cold gas efficiency. Additionally, this increase in external heat favourably impacts the Steam-Methane reforming reaction, boosting the H_2/CH_4 ratio. The thermodynamic results show that the plant achieves an energy efficiency of 44.17% and an exergy efficiency of 40.43%. The study also identifies the condenser as the primary source of energy loss, while the combustor experiences the greatest exergy loss.

Keywords: allothermal gasification; combined cycle; energy; exergy; Indian coal

1. Introduction

The population in modern times is growing exponentially, which raises the energy demand. The majority of power plants in India use coal as fuel. According to the Ministry of Power of India, 47.28% of electricity comes from coal-based power plants. As of 30 June 2024, India has an installed power generation capacity of 446,189.72 MW, as illustrated in **Figure 1** [1]. Fossil fuel burning and industrial gas emissions are releasing CO_2 into the atmosphere, which is responsible for at least 55% of global warming today. Hence, it is imperative to develop alternative plans for enhancing clean energy approaches, such as producing energy from renewable sources, raising overall plant efficiency, and applying clean technology such as gasification, fuel cells, and CO_2 capture. Gasification is a thermochemical process that converts carbonaceous feedstocks like coal and biomass into syngas with the help of gasifying mediums such as steam with air/oxygen and heat. Carbon monoxide (CO), hydrogen (H_2), and methane (CH_4) are the major combustible constituents of gasification. Due to the high conversion ratio of coal to H_2 and CO, Integrated Gasification Combined Cycle (IGCC) technology is considered one of the most important energy production technologies for the twenty-first century [2]. Several gasification methods are being investigated as a way to improve IGCC performance even further. Among different new techniques of gasification, "allothermal (heated indirectly)" gasification is one of them and is predicted to gain high interest among researchers. In allothermal gasification, the gasifier is heated by a heat exchanger inside the gasifier or by circulating hot bed material, which carries heat from other parts of the system [3]. A laboratory-scale gasifier is examined with concentrated Xe light radiation as an indirect heating source and steam as a gasifying medium, giving a carbon conversion of 88% after 120 min of irradiation [4]. Allothermal gasification of biomass using the heat of combustion of biomass micron fuel (BMF) produces product gas, which has an LHV of 12 MJ/Nm^3 [5]. Simulation of coal gasification coupled with a steam power plant using the gasifying medium as steam and oxy-steam shows net electrical efficiency of 21.38% and 9.80%, respectively [6]. Heat Pipe integrated Gasifier-Solid Oxide Fuel Cell-GT system shows a 55%–72% increase in electrical efficiency with anode gas as a gasifying agent [7].

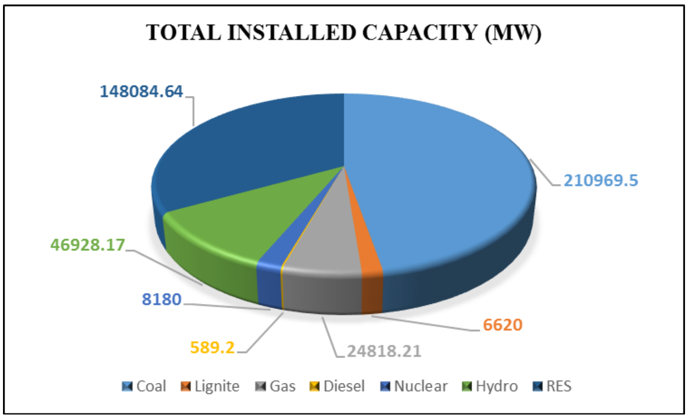

Figure 1. Total power production in India.

The above-mentioned literature shows that the allothermal gasification technique can increase the gasification efficiency in terms of the heating value of syngas and overall plant efficiency. In the present work, it is presented how the external heat of gasification affects the syngas composition and its effect on overall plant performance.

2. Methodology

The Cycle-Tempo software is used to perform an in-depth thermodynamic analysis of the proposed IGCC plant. [8]. This software models the plant as an interconnected system of mechanical and thermal components, which exchange mass and energy with each other and with the external environment. It employed the Gibbs energy minimization method to determine the gas compositions at the exits of the gasifier and compressor. The software operates based on key governing equations, including mass balance, energy balance, and exergy balance, as outlined below:

Mass balance: it refers to the fact to the fact that the total mass within a system remains constant over time unless there is an addition to or removal from the system. Mass balance is used to analyse processes where matter is flowing in and out of a system, such as chemical reactions or fluid flow.

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \tag{1}$$

Energy balance: it refers to energy conservation within a system. It involves tracking the amount of energy that enters and exits a system and the amount of energy generated or consumed within the system.

$$\sum_i \dot{m}_i h_i + \dot{Q}_{cv} = \sum_e \dot{m}_e h_e + \dot{W}_{cv} \tag{2}$$

Exergy balance: This concept considers the quality of energy within a system, by distinguishing between usable energy (exergy) and unusable energy (anergy).

$$\sum_i \dot{m}_i \Psi_i + \dot{X}_{heat} = \sum_e \dot{m}_e \Psi_e + \dot{W}_{cv} + \dot{I} \tag{3}$$

2.1. Plant configurations

Figure 2 illustrates the configuration of the IGCC plant, which includes a gasifier that uses Indian coal as a feedstock with steam as a gasifying medium. The ash separator receives the syngas from the gasifier, which mostly contains CO and H_2. It is worth mentioning that no syngas cooling unit is needed to attach to the model as the syngas temperature is lower than the ash softening temperature (1400 °C) [9]. It is assumed that 100% ash is separated and the clean syngas reaches the combustion chamber, where it is combusted with compressed air. After combustion, the hot flue gases expand in the gas turbine, producing power. After expansion, the flue gas passes through two heat exchangers, HX1 and HX2. Water is pumped at 10 bar through the heat exchanger (HX1), where it is converted into steam at 190 °C. The heat exchanger shown in the gasifier component of the Cycle-Tempo software is for cooling purposes of the syngas, where atmospheric water is passed through that heat exchanger and cooled down the syngas. But in this model, the bed material of the gasifier is heated by that heat exchanger. The simulation shows quite similar effects on the conversion of coal to syngas as that of indirect heating of bed material found in different literature [4,10].

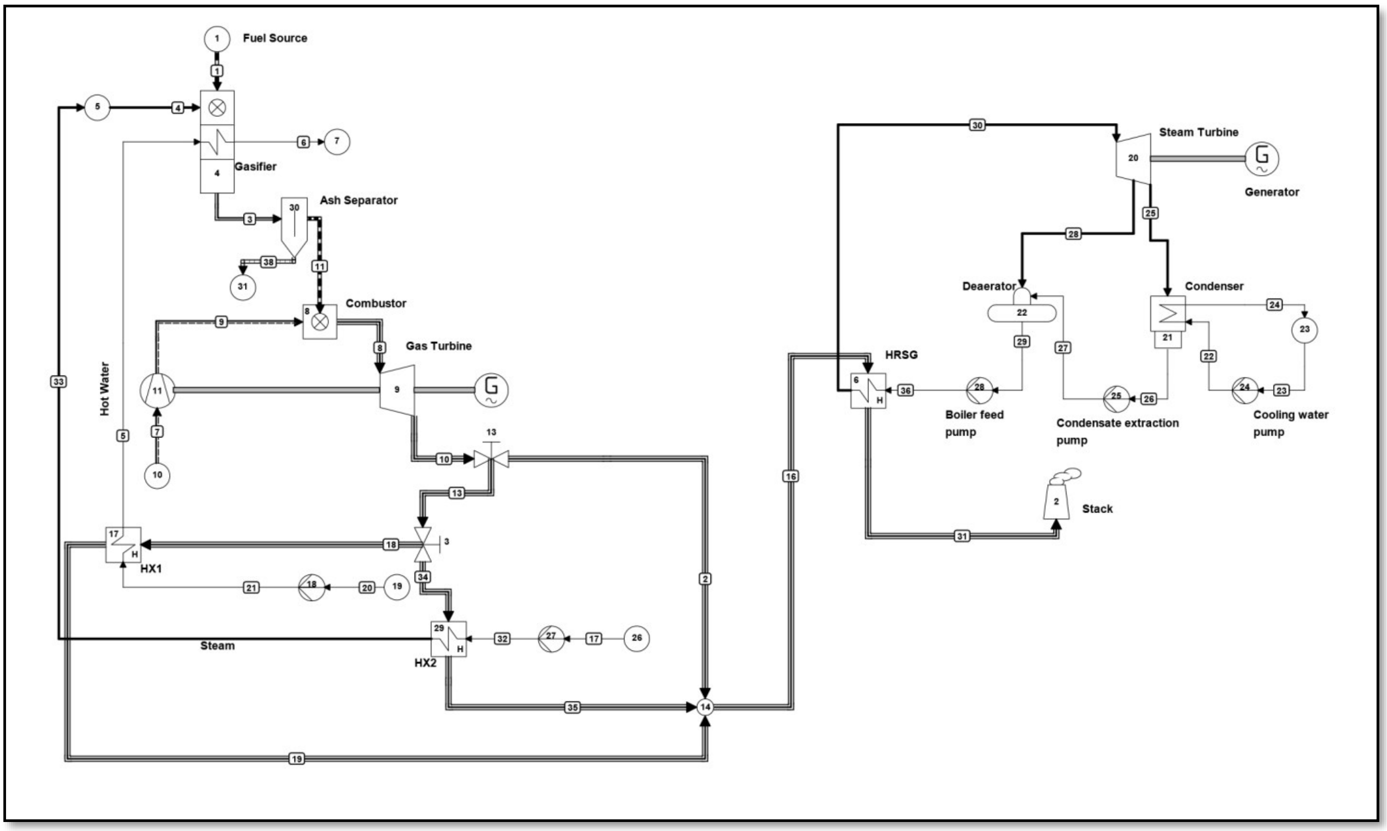

Figure 2. Layout of IGCC plant.

Therefore, the HX2 is used to heat the water for heating the bed material externally. The water flowing through pipe no 21 is heated up to 150 °C by the HX2 and leaves the HX of the gasifier at 50 °C rejecting heat to the gasifier. By harnessing the full capacity of the hot flue gas, the heat recovery steam generator (HRSG) converts the water from the feed pump into high-enthalpy steam. This steam then drives the turbine to produce electricity.

2.2. Fuel characteristics

The fuel considered for the proposed IGCC plant is Indian Coal. **Table 1** displays the heating values and composition of the Indian coal [11].

Table 1. Indian coal characteristics.

Ultimate analysis	**As dry basis (wt%)**
C	39.16
H	2.76
O	7.92
N	0.78
S	0.51
Ash	48.87
HHV (MJ/Kg)	15.83

2.3. Assumptions

In performing the chemical and thermodynamic evaluations of the gasifier and the proposed plant, the following assumptions have been applied:

Operating parameters of the gasifier:

1) Reaction pressure = 10 bar
2) Estimated pressure output = 10 bar
3) Steam-fuel ratio = 1

Gas turbine:

1) Turbine inlet pressure = 9 bar
2) Reaction temperature of combustor = 1000 ℃
3) Equivalence ratio = 1.5
4) Turbine outlet pressure = 1.01 bar

Steam turbine:

1) Turbine inlet pressure and temperature = 25 bar and 260 ℃
2) Bleed steam pressure = 3 bar
3) Condenser pressure = 25 kPa

2.4. Performance parameters

The following are the parameters that are used to calculate the results [12]:

$$\text{Energy efficiency} = \frac{\text{Net power output}}{\dot{m}_{\text{coal}} \times \text{heating value of coal}} \tag{4}$$

$$\text{Exergy efficiency } (\varepsilon) = \frac{\text{Net power output}}{\dot{m}_{\text{coal}} \times \text{coal specific exergy}} \tag{5}$$

$$\text{Cold gas efficiency} = \frac{\text{Heating value of product gas}}{\text{Heating value of feeding coal}} \tag{6}$$

3. Results and discussion

Table 2 reveals that the IGCC plant with external heat achieves an energy efficiency of 44.17% and an exergy efficiency of 40.43%, outperforming the configuration without external heat, which shows an energy efficiency of 43.17% and an exergy efficiency of 39.51%. This indicates that incorporating external heat into the gasifier improves both energy and exergy efficiencies, highlighting its beneficial impact on overall plant performance.

Table 2. Efficiencies of different plant.

Plant Type	Energy Efficiency (%)	Exergy Efficiency (%)
IGCC (With external heat)	44.17	40.43
IGCC (Without external heat)	43.17	39.51

3.1. Energy and exergy balance of IGCC plant (with external heat)

Energy losses are calculated using the ratio of heat rejected to the energy input from the fuel, while exergy losses are determined by the ratio of irreversibility to the exergy input. In the simulation, with 16,900 kw of external heat supplied to the gasifier at a reaction temperature of 650 °C, the net electrical power output reaches 120.9 MW on a lower heating value (LHV) basis. Of this, 24.89% of the total power is produced by the steam turbine. This integration of external heat not only boosts efficiency but also reduces the plant's overall water consumption.

The thermodynamic analysis shows that the IGCC plant achieves an overall energy efficiency of 44.17%. The major sources of energy loss are the condenser, which accounts for 27.43%, and the stack, contributing 26.79%. Minor losses are observed from ash at 0.88%, with the remaining 0.72% attributed to other losses by difference as shown in **Table 3**. This indicates that the condenser and stack are the primary areas where energy optimization could improve plant performance.

Table 3. Energy balance of the plant.

Components	In Percentage (%)
Energy Efficiency of plant	44.17
Losses	
Condenser	27.43
Stack	26.79
Ash	0.88
Others (By difference)	0.72

The exergy analysis of the IGCC plant shows an overall exergy efficiency of 40.43%. The combustor is identified as the largest source of exergy loss, accounting for 24.58%. Other significant losses occur in the steam generator for the gasifier (6.39%), HRSG (4.64%), gasifier (4.45%), and the stack (4.33%). Additional losses are observed in components such as the ash separator (3.78%), condenser (2.25%), gas turbine (1.34%), and steam turbine (0.91%), as shown in **Table 4**. The remaining 6.90% of losses are attributed to other factors by difference, highlighting the combustor as the primary area for potential efficiency improvement.

Table 4. Exergy balance of the plant.

Components	**In Percentage (%)**
Exergy Efficiency of plant	40.43
Losses	
Combustor	24.58
Steam generator for gasifier	6.39
HRSG	4.64
Gasifier	4.45
Stack	4.33
Ash Separator	3.78
Condenser	2.25
Gas Turbine	1.34
Steam Turbine	0.91
Others (by difference)	6.90

3.2. Parametric analysis of the plant

The parametric analysis in the study investigates the impact of external heat on various performance parameters of the IGCC plant. It reveals that increasing external heat supplied to the gasifier enhances the lower heating value (LHV) of syngas, improves the hydrogen-to-methane (H_2/CH_4) ratio, and boosts overall plant efficiency. The higher external heat input favors the endothermic steam-methane reforming reaction, resulting in a syngas with a higher hydrogen content and reduced methane. Additionally, the cold gas efficiency of the plant increases by 3.01% when 16,900 kw of heat is supplied to the gasifier, demonstrating the positive influence of external heat on the thermodynamic performance of the plant. This analysis highlights the critical role of external heat in optimizing syngas composition and improving overall plant efficiency.

3.2.1. Effect of external heat on LHV of syngas

Figure 3 shows how the lower heating value (LHV) of syngas increases as the external heat supplied to the gasifier rises. As more heat is added, the gasification process becomes more efficient, resulting in a higher energy content in the syngas produced. The graph demonstrates a clear positive relationship between the heat supplied and the LHV, highlighting the benefits of external heat in enhancing syngas quality.

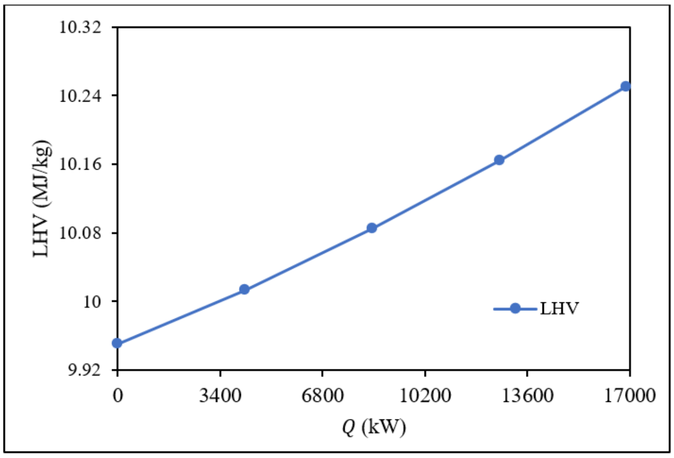

Figure 3. Effect of external heat on LHV of syngas.

3.2.2. Effect of external heat on H_2/CH_4 ratio

Figure 4 illustrates the effect of external heat on the hydrogen to methane (H_2/CH_4) ratio in the syngas. As the external heat input increases, the H_2/CH_4 ratio also rises. This is due to the steam-methane reforming reaction, which is endothermic and benefits from the additional heat. As a result, more hydrogen is produced, and the methane content decreases, improving the syngas composition for energy generation.

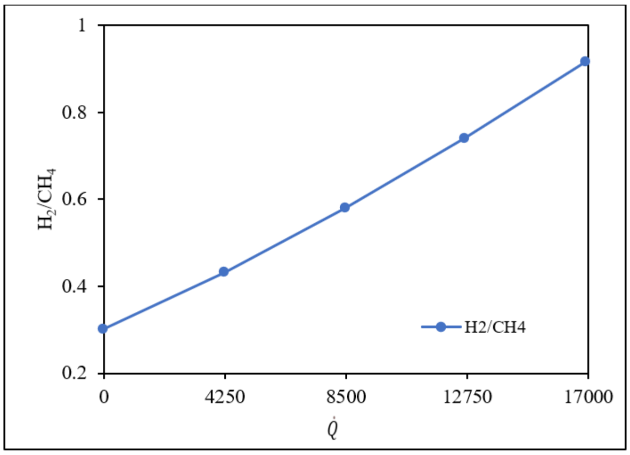

Figure 4. Effect of external heat on H_2/CH_4 ratio.

3.2.3. Effect of external heat on efficiency of the plant

Figure 5 presents the increase in plant efficiency (η) as external heat supplied to the gasifier is raised. The graph shows that, as the heat input increases, the net efficiency of the IGCC plant improves. This is because the enhanced syngas composition, particularly with higher hydrogen content, boosts the overall performance of the power generation cycle, leading to a higher net efficiency. The figure emphasizes the role of external heat in maximizing plant efficiency.

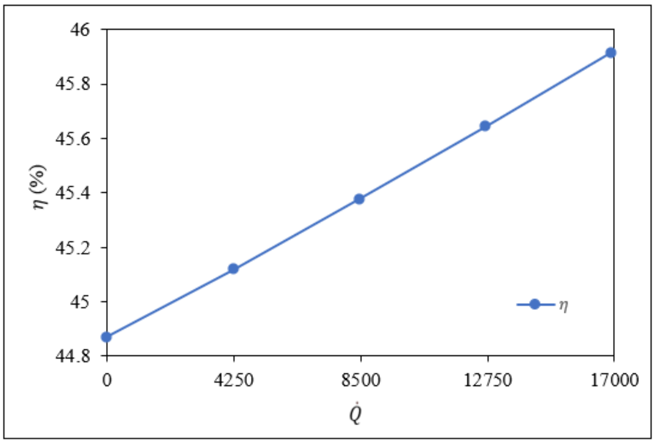

Figure 5. Effect of external heat on plant efficiency.

3.3. Validation of gasifier

To validate the proposed model, the results of two equilibrium gasification models from two different literatures are compared. The literature models are simulated in Aspen Plus software and Cycle-Tempo software, respectively [13,14]. In both, the literature shows that gasification of sawdust has been done with 10% moisture at a temperature of 800 °C. A simulation using the suggested model with the same gasification condition using sawdust as fuel was run for this comparison. **Figure 6** shows the comparison of syngas composition between the proposed model and literature data. The syngas composition of the developed gasifier model closely resembles the syngas composition of literature. Molar fraction of methane is not considered here as the value comes out to only 0.02%, which is the same as the above-mentioned literature.

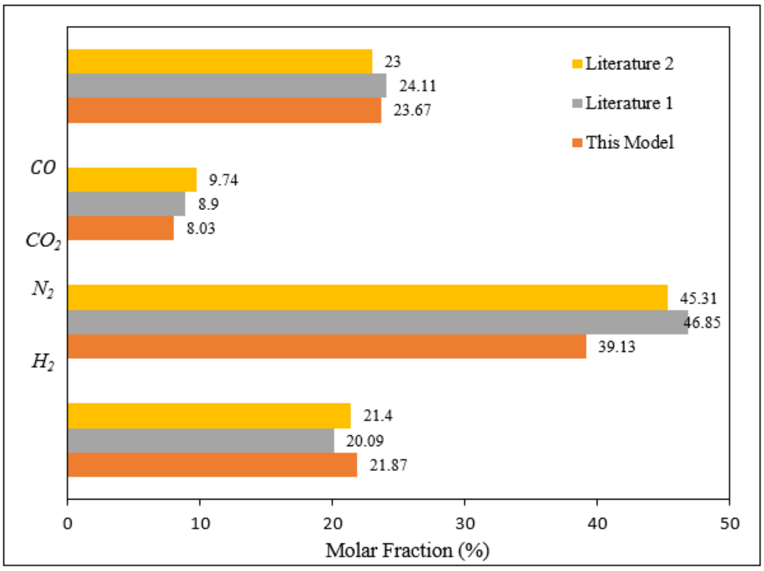

Figure 6. Comparison of syngas composition with literature data.

4. Conclusions

This study provides a comprehensive thermodynamic evaluation of an IGCC power plant using allothermal gasification. The findings demonstrate that applying external heat to the gasification process significantly enhances the syngas quality and overall plant performance. Specifically, utilizing steam as a gasifying agent and incorporating external heat increased the lower heating value (LHV) of the syngas and improved the hydrogen-to-methane (H_2/CH_4) ratio, which contributed to greater energy conversion efficiency. The energy and exergy efficiencies of the IGCC plant with external heat were measured at 44.17% and 40.43%, respectively, which represents an improvement over configurations without external heat. These gains underscore the thermodynamic benefits of integrating external heat into the gasification process. However, energy losses in the system were primarily observed in the condenser and stack, accounting for 27.43% and 26.79% of total losses, respectively. Exergy losses were most significant in the combustor, contributing to 24.58% of the total irreversibility. These areas present opportunities for optimization to further enhance the plant's efficiency. Parametric analysis further demonstrated that increasing the external heat supplied to the gasifier boosts syngas quality and plant efficiency by favoring endothermic reactions like steam-methane reforming, which increase hydrogen production.

In conclusion, the integration of external heat in allothermal gasification offers a promising pathway to improve both the energy and exergy efficiency of IGCC power plants. The reduction in water consumption and enhanced syngas composition provides additional environmental and operational benefits, making it a viable approach for optimizing future coal-based energy systems.

Author contributions: Conceptualization, SG; methodology, NKC; software, NKC and SG; validation, NKC; data curation, SK; writing—original draft preparation, NKC; writing—review and editing SK. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Abbreviations

HX	Heat Exchanger
h	Specific Enthalpy (kJ/kg)
Ψ	Exergy (kJ/kg)
I	Irreversibility (kW)
P	Pressure (bar)
N_2	Nitrogen
S	Sulfur
C	Carbon
H_2O	Water
O_2	Oxygen
HHV	Higher Heating Value (MJ/kg)
$\dot{m}_w$	Mass Flow Rate of Water (kg/s)
$\dot{Q}$	External Heat Flow Rate (kW)

References

1. Executive summary power sector. Available online: https://cea.nic.in/wp-content/uploads/executive/2024/07/Executive_Summary_June_2024.pdf (accessed on 8 August 2024).
2. Promes EJO, Woudstra T, Schoenmakers L, et al. Thermodynamic evaluation and experimental validation of 253 MW Integrated Coal Gasification Combined Cycle power plant in Buggenum, Netherlands. Applied Energy. 2015; 155: 181-194. doi: 10.1016/j.apenergy.2015.05.006
3. Bhaskar T, Balagurumurthy B, Singh R, et al. Thermochemical Route for Biohydrogen Production. Biohydrogen. 2013; 285-316. doi: 10.1016/b978-0-444-59555-3.00012-x
4. Gokon N, Izawa T, Abe T, et al. Steam gasification of coal cokes in an internally circulating fluidized bed of thermal storage material for solar thermochemical processes. International Journal of Hydrogen Energy. 2014; 39(21): 11082-11093. doi: 10.1016/j.ijhydene.2014.05.124
5. Cheng G, Li Q, Qi F, et al. Allothermal gasification of biomass using micron size biomass as external heat source. Bioresource Technology. 2012; 107: 471-475. doi: 10.1016/j.biortech.2011.12.074
6. Karellas S, Panopoulos KD, Panousis G, et al. An evaluation of Substitute natural gas production from different coal gasification processes based on modeling. Energy. 2012; 45(1): 183-194. doi: 10.1016/j.energy.2012.03.075
7. Santhanam S, Schilt C, Turker B, et al. Thermodynamic modeling and evaluation of high efficiency heat pipe integrated biomass Gasifier–Solid Oxide Fuel Cells–Gas Turbine systems. Energy. 2016; 109: 751-764. doi: 10.1016/j.energy.2016.04.117
8. Cycle-Tempo release 5.1.7, Delft University of Technology. Available online: https://asimptote.com/cycle-tempo/ (accessed on 10 June 2024).
9. Ozer M, Basha OM, Stiegel G, et al. Effect of coal nature on the gasification process. Integrated Gasification Combined Cycle (IGCC) Technologies. 2017; 257-304. doi: 10.1016/b978-0-08-100167-7.00007-x
10. Suárez-Almeida M, Gómez-Barea A, Ghoniem AF, et al. Solar gasification of biomass in a dual fluidized bed. Chemical Engineering Journal. 2021; 406: 126665. doi: 10.1016/j.cej.2020.126665
11. Choudhary NK, Khankari G, Karmakar S. Waste heat utilization using organic rankine cycle from a pressurized pulverized combined cycle power plant. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2024; 238(5): 922-933. doi: 10.1177/09576509241240013
12. Choudhary NK, Deep AP, Karmakar S. Thermodynamic Analysis of Integrated Gasification Combined Cycle Integrated with Organic Rankine Cycle for Waste Heat Utilization. Waste and Biomass Valorization. 2024; 15(6): 3691-3709. doi: 10.1007/s12649-023-02391-2
13. Okati A, Khani MR, Shokri B, et al. On the operating parameters for hydrogen-rich syngas production in a plasma co-gasification process of municipal solid wastes and polypropylene using a constrained model in Aspen plus. Journal of the Energy Institute. 2023; 107: 101173. doi: 10.1016/j.joei.2023.101173
14. Altafini CR, Wander PR, Barreto RM. Prediction of the working parameters of a wood waste gasifier through an equilibrium model. Energy conversion and management. 2003; 44(17): 2763-2777. doi: 10.1016/S0196-8904(03)00025-6