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Optimization and exergy-energy-economic analysis of a modified Rankine cycle utilizing waste heat recovery from clinker processes in a cement plant

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Extended Abstract

Introduction

The cement manufacturing industry is one of the most energy-intensive industrial sectors, involving high-temperature processes such as raw material heating, calcination, clinker formation, and clinker cooling. A considerable portion of the energy supplied to cement production processes is ultimately released as waste heat, particularly from hot clinker and the clinker cooling section. Recovering and utilizing this otherwise wasted thermal energy can significantly improve overall energy efficiency, reduce fossil-fuel consumption, lower operating costs, and mitigate environmental impacts. One of the promising approaches for converting industrial waste heat into useful energy is the integration of a Rankine cycle with the cement production process. Previous studies have demonstrated the considerable potential of waste heat recovery in cement plants using conventional steam Rankine cycles, Organic Rankine Cycles (ORCs), Kalina cycles, and combined thermodynamic configurations. However, the performance of such systems strongly depends on operating conditions, working-fluid properties, and the configuration of individual components. In particular, the turbine inlet and outlet pressures and the amount of heat supplied to the boiler can substantially influence energy efficiency, exergy destruction, and the economic performance of the system. In this study, an improved Rankine cycle integrated with the clinker cooling process of a cement plant is proposed. The main objective is to recover waste heat from the clinker cooling section and utilize it for simultaneous power and heat generation. In addition to conventional energy and exergy analyses, an economic assessment is performed to evaluate the feasibility of the proposed configuration. Furthermore, a genetic algorithm is employed to optimize the major operating parameters of the system. The turbine inlet pressure, turbine outlet pressure, and boiler heat input are considered as the principal optimization variables, while energy and exergy efficiencies are used as the main performance criteria. The effect of incorporating an ejector into the Rankine cycle is also investigated to determine its influence on turbine operating temperatures, boiler heat input, and exergy destruction.

2. Materials and Methods

The proposed system is based on the recovery of thermal energy from the clinker cooling process in a cement plant. Hot clinker discharged from the rotary kiln enters the clinker cooler, where cold air is introduced to reduce its temperature. As a result of this cooling process, a hot air stream containing a significant amount of recoverable thermal energy is generated. In the proposed configuration, a portion of this waste heat is directed toward the boiler of the Rankine cycle, while the remaining available heat is utilized through a heat exchanger. A thermal separator is employed to distribute the recovered heat between these two pathways. The thermodynamic model consists principally of a boiler, turbine, ejector, condenser, pump, and heat exchanger. The recovered heat from the clinker cooling section is transferred to the working fluid in the boiler. The high-pressure and high-temperature vapor generated in the boiler expands through the turbine, producing mechanical work. The turbine exhaust is subsequently introduced into an ejector, where it interacts with another vapor or gas stream originating from the waste-heat recovery section. The ejector reduces the downstream pressure and assists in establishing suitable conditions for the subsequent condensation process. Energy analysis is performed using the principles of mass and energy conservation. The main thermodynamic parameters, including turbine work, pump work, heat input, heat rejection, net work output, and thermal efficiency, are calculated based on the thermodynamic properties of the working fluid. Exergy analysis is subsequently performed using the first and second laws of thermodynamics. Physical exergy and exergy destruction are determined for the main components, allowing the sources of irreversibility and thermodynamic inefficiency to be identified. The overall exergy efficiency of the cycle is then evaluated. An exergoeconomic analysis is also conducted to investigate the economic implications of thermodynamic losses. The capital recovery factor, operational and maintenance costs, capital costs of the main components, and total system cost are calculated. The economic model considers an interest rate of 12% and an operating period of 20 years. To improve the system performance, a genetic algorithm is employed. The optimization variables include **the** turbine inlet pressure, turbine outlet pressure, and boiler heat input. The turbine inlet pressure is varied within the range of 100–1500 kPa, the turbine outlet pressure between 10–200 kPa, and the boiler heat input between 1000 and 2000 kW. Energy efficiency and exergy efficiency are considered the principal objective functions of the optimization process. The numerical model is also validated by comparing the calculated waste-heat characteristics with previously published reference data. The differences between the predicted and reference values are reported to be very small and within the acceptable experimental error range, indicating that the developed thermal model provides an appropriate basis for further thermodynamic and optimization analyses.

. 3. Results and Discussion

The initial thermodynamic assessment demonstrates that the proposed system can effectively utilize the waste heat generated during clinker cooling. The energy and exergy analyses provide information regarding the work production, heat transfer, and irreversible losses occurring in the different components of the cycle. The exergy analysis is particularly important because it identifies the locations where the quality of energy is irreversibly degraded and therefore provides a basis for improving the system configuration. The initial configuration provides an energy efficiency of approximately 23% and an exergy efficiency of approximately 22.68%. These values demonstrate the potential of recovering clinker waste heat for useful energy production, while also indicating that considerable opportunities remain for improving the thermodynamic performance of the system. The genetic-algorithm optimization produces a substantial improvement in the overall performance. According to the optimized results reported in the article, the energy efficiency increases to 29.63%, while the exergy efficiency reaches 37.03%. The optimized operating conditions include a turbine inlet pressure of approximately 800 kPa, compared with the initial value of 1250 kPa, and a turbine outlet pressure of approximately 48 kPa, compared with the initial value of about 102.4 kPa. The optimized boiler heat input is approximately 1621 kW. These results demonstrate that appropriate adjustment of the operating pressures and heat input can significantly improve the conversion of waste heat into useful energy and reduce thermodynamic irreversibilities. A particularly important finding concerns the influence of the ejector on the Rankine cycle. Incorporating the ejector reduces the turbine inlet temperature from approximately 429.9°C to 352.3°C, corresponding to a reduction of nearly 18–20%. The turbine outlet temperature is also reduced from approximately 111.1°C to 80.3°C. The reduction in turbine inlet temperature decreases the thermal load imposed on the turbine blades and makes the system more compatible with lower-temperature waste-heat sources. At the same time, the lower turbine outlet temperature reduces the amount of heat rejected in the condenser and may increase the possibility of recovering useful thermal energy downstream. The incorporation of the ejector also results in a considerable reduction in the required boiler heat input. The reported results indicate an approximately 22% reduction in boiler heat input compared with the basic Rankine cycle. Furthermore, exergy destruction is reduced in the modified configuration, which indicates a reduction in entropy generation and thermodynamic irreversibility. Consequently, the ejector improves not only the energy utilization of the system but also the quality of energy conversion from an exergy perspective. The economic analysis further indicates that the thermodynamic improvements should be considered together with the costs associated with the main components, including the turbine, pump, ejector, condenser, and boiler. The use of a capital recovery factor and the evaluation of capital, operational, and maintenance costs provide a framework for assessing the economic feasibility of the proposed waste-heat recovery system. Thus, the proposed configuration can be considered not merely as a thermodynamic optimization problem, but as an integrated thermoeconomic optimization in which energy efficiency, exergy destruction, and economic performance must be considered simultaneously. Overall, the results demonstrate that recovering waste heat from clinker cooling and integrating it with a modified Rankine cycle can improve the utilization of energy that would otherwise be lost to the environment. The optimization of operating pressures and boiler heat input further enhances system performance, while the ejector contributes to reductions in turbine temperatures, boiler heat demand, and thermodynamic irreversibility. These improvements are particularly relevant for cement plants because the process provides a continuous source of high-temperature waste heat that can be converted into useful electrical and thermal energy.

4. Conclusions

In this study, a modified Rankine cycle integrated with the waste-heat stream of the clinker cooling section of a cement plant was thermodynamically, exergetically, economically, and computationally investigated. The principal objective was to recover waste thermal energy from clinker cooling and utilize it for useful power and heat generation while improving the overall efficiency of the energy-conversion system. The results showed that the initial configuration achieved an energy efficiency of approximately 23% and an exergy efficiency of approximately 22.68%. Application of the genetic-algorithm optimization improved the energy efficiency to 29.63% and the exergy efficiency to 37.03%. The optimized turbine inlet and outlet pressures were approximately 800 and 48 kPa, respectively, while the optimized boiler heat input was approximately 1621 kW. These results confirm the significant influence of operating conditions on the thermodynamic performance of the proposed cycle. The incorporation of an ejector into the Rankine cycle was also found to be beneficial. The ejector reduced the turbine inlet temperature from approximately 429.9°C to 352.3°C and the turbine outlet temperature from approximately 111.1°C to 80.3°C. In addition, the required boiler heat input decreased by approximately 22%, while the thermodynamic irreversibility associated with exergy destruction was also reduced. These findings demonstrate that the ejector-assisted configuration can improve energy utilization, reduce thermal losses, and enhance the flexibility of the system for utilizing industrial waste-heat sources. Therefore, the integration of waste-heat recovery from clinker cooling with a modified Rankine cycle can be considered a technically promising approach for improving energy efficiency and reducing energy costs and environmental impacts in cement manufacturing. The study suggests that further research should investigate the use of nanofluids as alternative working fluids, recovery of additional turbine waste heat for desalination through MED and MSF systems, and the application and comparison of different optimization algorithms.

Keywords: exergy, combined heat and power generation system, cement production plant, system performance optimization, enhanced Rankine thermal cycle.

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