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Fuel Consumption Optimization in the Main Furnace of the Fluid Catalytic Cracking Unit Using Numerical Simulation and Operational Data

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1. ABSTRACT

Optimizing fuel consumption in industrial furnaces plays a crucial role in reducing energy costs and minimizing environmental emissions. This study focuses on improving fuel efficiency in the main furnace of the RFCC unit at Imam Khomeini Shazand Refinery. A combined approach of numerical simulation using Aspen EDR and analysis of operational data from the Distributed Control System (DCS) was employed. Key parameters investigated include excess air ratio, refractory lining thickness, and the application of a 100 mm fibrous ceramic coating. Results indicate that increasing excess air from 15% to 50% leads to a 17.6% rise in fuel consumption and a 2.7% reduction in thermal efficiency. Conversely, the application of a 100 mm ceramic coating resulted in a 7.2% fuel saving and a 5.4 percentage-point improvement in efficiency. Multi-objective optimization using a genetic algorithm identified optimal operating conditions at 5.84% oxygen concentration, 60% damper opening, and a feed rate of 450 m³/h, yielding a 1.8% improvement in thermal efficiency compared to baseline operation. The findings provide practical and cost-effective strategies for enhancing energy efficiency in industrial furnaces.

Keywords: Fuel Consumption Optimization, Numerical Simulation, Cylindrical Furnace, Genetic Algorithm, Ceramic Fiber Blanket**.**

2. INTRODUCTION

Fluid Catalytic Cracking (FCC) units are among the largest energy consumers in refineries. The main furnace, such as the H-1502 furnace at Shazand Refinery, often operates sub-optimally, leading to high fuel costs and significant thermal losses through walls and flue gases [1, 2]. While previous studies have utilized Computational Fluid Dynamics (CFD) or machine learning for combustion optimization [3], a gap exists in integrating high-fidelity process simulation with real-time operational data and intelligent multi-objective optimization for practical solutions. This study's primary innovation lies in combining three complementary methodologies: numerical simulation with Aspen EDR, operational data analysis from the DCS, and GA-based optimization. The main objectives were to diagnose performance bottlenecks, quantify the impact of key operational and design parameters, and provide a data-driven optimization strategy for the H-1502 furnace to reduce fuel consumption and enhance thermal efficiency, thereby offering measurable and cost-effective strategies for industrial application.

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3. MATERIALS AND METHODS

The research methodology was structured in three phases. First, operational data from the plant's DCS were collected over 12 months and analyzed to establish a performance baseline and identify critical inefficiencies, such as high excess oxygen and elevated skin temperatures.

Second, a detailed numerical model of the H-1502 furnace (Figure1) was developed and validated using Aspen EDR (Version 11). The model was based on design data from LINDE [4] and operational boundaries. To conduct a comprehensive sensitivity analysis, key parameters were varied over wide ranges. The excess air ratio (λ) was adjusted between 1% and 50%, insulation thickness (castable refractory) ranged from 120 mm to 190 mm, wall emissivity (ε) varied from 0.1 to 0.9, and the insulation material was compared between castable refractory and ceramic fiber blanket (CFB). Combustion was modeled, and heat transfer was calculated using well-established correlations, such as the Sieder–Tate equation for turbulent flow. The model assumptions included steady-state conditions and complete combustion, and the results were validated against field measurements obtained using a Testo 340 gas analyzer. Third, multi-objective optimization was performed using a Genetic Algorithm implemented in Python (with Pandas, NumPy, and Scikit-learn libraries). The objective was to minimize fuel consumption while maximizing thermal efficiency. The input variables were oxygen concentration, damper opening, and feed flow rate.

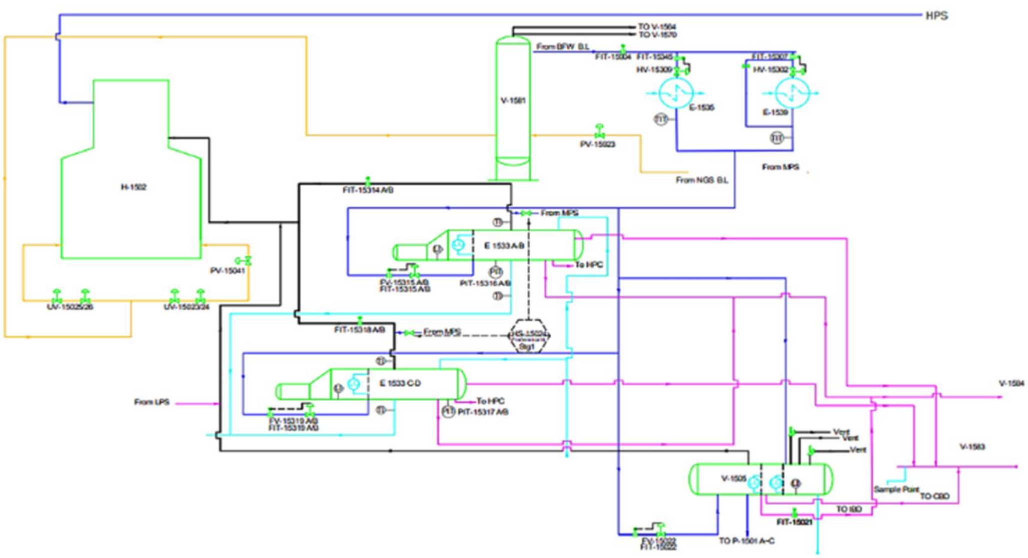

Figure1. Flow diagram of the steam generation system of Unit 1502

4. RESULTS AND DISCUSSION

4.1. Effect of Excess Air Ratio

Increasing the excess air ratio from 1% to 50% resulted in a decrease in the adiabatic combustion temperature from 838°C to 784°C. This temperature reduction occurs due to increased competition between the fuel energy and the larger volume of excess air; the additional air absorbs more heat energy, thereby lowering the combustion gas temperature. Simultaneously, wall and exhaust heat losses increased from 27.17% to 35.53%, as the cooler flue gases and higher airflow carried more thermal energy away to the surroundings and the stack. Consequently, combustion efficiency decreased from 72.67% to 64.22%, corresponding to an overall 11.6% reduction in thermal cycle efficiency. These results indicate that excessive air supply not only leads to energy loss but also negatively affects furnace efficiency. On the other hand, insufficient air can cause incomplete combustion, reducing thermal performance. Therefore, precise control of the excess air ratio, considering both operational conditions and furnace design, is essential to optimize fuel consumption and minimize heat losses. Moreover, maintaining a constant fuel consumption rate of 1700 kg/h across all scenarios confirms that the observed variations in efficiency and temperature are solely due to changes in excess air ratio, while other parameters remained constant. This analysis highlights the importance of accurate excess air control and the use of advanced monitoring systems to enhance the efficiency of industrial furnaces. This underscores the critical need for precise control of combustion air, as per API 560 standards [5].

4.2. Effect of Insulation Type and Thickness

Increasing the refractory insulation thickness from 120 mm to 190 mm resulted in only a 1.34% improvement in overall furnace efficiency (from 69.15% to 70.49%). This marginal efficiency gain does not justify the substantial costs associated with dismantling the existing lining, procuring new materials, and installing a thicker castable refractory layer. Therefore, increasing the thickness of castable refractories is not recommended as a cost-effective optimization strategy. Instead, emphasis should be placed on replacing the existing refractory with lighter insulation materials featuring lower thermal conductivity, such as a 100 mm Ceramic Fiber Blanket (CFB). As summarized in Table 1, this alternative provides a significantly greater improvement in furnace efficiency and fuel economy at a considerably lower cost, making it a practical and economically viable solution for enhancing the thermal performance of industrial furnaces.

Table 1. Performance comparison of insulation materials

Parameter	Castable Refractory	Ceramic Fiber Blanket	Change
Fuel Flow (kg/h)	2150	1995	-155 kg/h
Overall Efficiency (%)	69.54	74.3	+4.76 pp
Wall Heat Loss (%)	7.64	3.67	-48%
Parameter	Castable Refractory	Ceramic Fiber Blanket	Change

This substitution led to 7.2% fuel savings and a significant boost in efficiency, primarily due to the superior thermal resistance of the ceramic fiber.

4.3. Multi-Objective Optimization and Field Implementation

In this study, the performance of the industrial furnace H-1502 was optimized through the integration of engineering simulation (Aspen EDR), operational data analysis (DCS), and a genetic algorithm. The results showed that reducing excess air from 50% to 15% led to a 17.6% reduction in fuel consumption and a decrease in flue gas temperature from 317°C to 272°C. Replacing the conventional refractory insulation with 100 mm nano-structured ceramic coating reduced wall heat losses by 48% and achieved an annual fuel saving of about 1,350 tons. The optimal operating conditions—5.84% oxygen concentration, 60% damper opening, and a feed flow rate of 450 m³/h—resulted in a 1.7% increase in efficiency and an 18% reduction in fuel usage. Although the initial implementation cost is estimated to be 35–40% higher than conventional systems, the payback period is projected at 18–22 months, with additional benefits including a 25–30% increase in equipment lifespan and a 15% reduction in maintenance costs.

5. CONCLUSION

This study investigated and optimized the performance of the H-1502 furnace in the RFCC unit of the Imam Khomeini Shazand refinery, providing practical and implementable strategies to improve energy efficiency through the integration of numerical simulation in Aspen EDR, operational data analysis from the distributed control system (DCS), and multi-objective optimization using a genetic algorithm. Key findings include:

- Reducing excess air from 50% to 15% led to a 17.6% decrease in fuel consumption and a reduction in flue gas temperature from 317°C to 272°C.
- Replacing conventional insulation with a 100 mm nano-structured ceramic coating ($\varepsilon = 0.9$) reduced wall heat losses, lowered external surface temperature by 39%, and achieved an annual fuel saving of approximately 1,350 tons.
- Multi-objective optimization using the genetic algorithm identified the optimal operating point at a feed flow of 450 m³/h, oxygen concentration of 5.84%, and damper opening of 60%, resulting in an 18% reduction in fuel consumption and a 1.7% increase in efficiency.
- Implementation of the optimized model under real operating conditions confirmed improvements in furnace efficiency, reduced fuel consumption, and increased steam production.

This study demonstrates innovation through the integration of engineering simulation, operational data analysis, and intelligent optimization, while maintaining compatibility with existing control systems. Limitations include the applicability of results to furnaces using different fuels and the need for preliminary economic evaluation. Based on the findings, a pilot implementation over 15–20% of the furnace surface for 6–8 weeks, with careful monitoring of key parameters, is recommended to verify the effects of optimization prior to full-scale deployment. Ultimately, the research shows that optimizing operational parameters and improving insulation systems can significantly reduce fuel consumption and enhance the thermal efficiency of industrial furnaces.

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