Mechanics

ANALYSIS OF ENERGY LOSS MECHANISMS IN PROCESS FURNACES AND ENGINEERING STRATEGIES FOR THERMAL EFFICIENCY ENHANCEMENT

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Abstract. Process furnaces constitute a critical component of thermal energy consumption in petroleum refining systems, where even minor efficiency deviations can result in considerable fuel and economic losses. The present study investigates the principal mechanisms responsible for energy dissipation in fired process heaters and evaluates engineering-oriented measures for their mitigation. A structured heat balance formulation is applied to quantify losses associated with flue gases, external wall radiation, air leakage, and incomplete combustion phenomena. The analysis emphasizes the thermodynamic sensitivity of furnace efficiency to excess air ratio and exhaust gas temperature. Based on the obtained analytical relationships, practical improvement pathways are outlined, including combustion control optimization, enhancement of refractory insulation performance, and integration of heat recovery technologies. The proposed assessment framework offers a technically grounded basis for operational diagnostics and efficiency-oriented decision-making in refinery furnace systems.

Keywords. *Process furnace, Fired heater efficiency, Energy dissipation, Heat balance methodology, Combustion performance.*

Introduction. Process furnaces represent one of the primary thermal energy consumers in petroleum refining and petrochemical facilities. In many refinery units, fired heaters operate continuously under high-temperature conditions, making their thermal performance directly linked to fuel utilization, operational stability, and environmental impact [1, pp. 25–42]. Even marginal inefficiencies in combustion or heat transfer processes may lead to substantial cumulative energy losses over prolonged operating periods. Heat transfer in process furnaces is predominantly governed by radiation, particularly within the high-temperature combustion zone [2, pp. 87–105]. The interaction between flame characteristics, furnace geometry, and heat-absorbing surfaces determines the distribution of thermal flux inside the radiant section. In addition to useful heat absorbed by process tubes, a significant portion of supplied energy leaves the system in the form of stack gas losses, wall radiation, and unburned chemical energy [3, pp. 112–130]. Among the various operational parameters, the excess air ratio plays a decisive role in controlling combustion completeness and flue gas temperature. While insufficient air may result in incomplete combustion and CO formation, excessive air increases flue gas mass flow and reduces overall efficiency [4, pp. 155–172]. Consequently, achieving a balanced combustion regime is essential for stable furnace performance. Industrial standards for refinery fired heaters emphasize the importance of proper heat balance evaluation and efficiency monitoring [5, pp. 286–305]. However, in practical operation, energy losses are often distributed across multiple mechanisms rather than originating from a single dominant factor. A systematic analytical assessment is therefore required to identify the most influential contributors to efficiency degradation [6]. The present study aims to examine the principal energy loss mechanisms in process furnaces through a structured heat balance approach and to evaluate technically feasible strategies for reducing thermal inefficiencies in refinery applications.

Research objective and problem statement. Despite decades of technological development in combustion systems, process furnaces in refinery environments continue to operate with measurable thermal inefficiencies. While modern control systems provide real-time monitoring of oxygen concentration and flue gas temperature, performance evaluation in many facilities remains limited to overall efficiency indicators or fuel consumption tracking [7]. Such aggregated metrics do not reveal the internal distribution of energy losses and therefore do not support targeted corrective actions. A fundamental engineering challenge lies in the multi-mechanism nature of energy dissipation in fired heaters [8]. Thermal input supplied through fuel combustion is redistributed through several parallel pathways: useful heat transfer to process tubes, sensible heat discharge through flue gases, conductive and radiative losses through furnace walls, and minor chemical losses associated with incomplete combustion [9, pp. 360–382]. These mechanisms are interdependent rather than isolated. For instance, adjustment of excess air ratio may reduce incomplete combustion losses but simultaneously increase stack-related heat discharge. Consequently, isolated parameter tuning without systemic evaluation may unintentionally shift losses from one mechanism to another rather than improving overall efficiency [10, pp. 28–40]. Another complexity arises from the operational variability of refinery furnaces. Load fluctuations, fuel composition changes, and gradual refractory degradation alter thermal behavior over time. In such conditions, efficiency deterioration may occur gradually and remain undetected if not analyzed through a structured energy balance framework. Therefore, a method capable of separating operational losses from structural losses becomes essential for rational performance diagnostics.

The central problem addressed in this study is the absence of a transparent and practically applicable analytical model that quantifies individual energy loss components using accessible operational parameters. While advanced numerical simulations provide detailed insights, their implementation requires computational resources and specialized expertise, limiting their applicability for routine industrial diagnostics [11]. There exists a practical need for an intermediate-level analytical tool that bridges theoretical thermodynamic principles and everyday engineering decision-making. Accordingly, the primary objective of this research is to formulate and apply a heat balance–based methodology that identifies dominant loss mechanisms in process furnaces and evaluates their relative impact on overall thermal efficiency. Particular emphasis is placed on the thermodynamic sensitivity of stack losses to excess air ratio and flue gas temperature, as these parameters are directly measurable and adjustable in refinery operation [12]. By establishing quantitative relationships between operating variables and efficiency degradation, the study aims to provide a structured foundation for performance improvement strategies without reliance on complex numerical modeling.

Furthermore, the research seeks to clarify the interaction between operational control variables and structural design characteristics. Through analytical decomposition of energy flows, the proposed framework enables differentiation between losses that can be mitigated through combustion optimization and those requiring mechanical or insulation improvements. This distinction is critical for prioritizing technical interventions and allocating maintenance resources efficiently.

In summary, the study addresses both a diagnostic gap and a methodological need within refinery furnace performance evaluation. By integrating thermodynamic principles with practical engineering considerations, it aims to transform efficiency analysis from a descriptive indicator-based practice into a mechanism-oriented assessment approach.

Methods of problem solution. The performance assessment of a process furnace requires a structured decomposition of supplied chemical energy into useful and dissipative components. Under steady-state operation, and neglecting transient accumulation effects, the conservation of energy principle may be expressed in generalized form as:

$$Q_{fuel} = Q_{abs} + Q_{loss} \tag{1}$$

For engineering evaluation, the total loss term is further separated into physically interpretable mechanisms:

$$Q_{fuel} = Q_{abs} + Q_{stack} + Q_{wall} + Q_{leak} + Q_{unburned} \tag{2}$$

Where:
Q_{fuel} – heat given by fuel combustion,
Q_{abs} – heat transferred to process fluid,

Q_{stack} – sensible heat removed with flue gases,
Q_{wall} – conductive and radiative heat transfer through furnace casing,
Q_{leak} – energy impact of air infiltration,
$Q_{unburned}$ – chemical losses due to incomplete combustion.

Thermal efficiency is defined as:

$$\eta = \frac{Q_{abs}}{Q_{fuel}} * 100\% \tag{3}$$

Where:
η – thermal efficiency.

This formulation enables identification of dominant loss contributors without requiring numerical simulation. Stack losses represent the largest fraction of energy dissipation in most fired heaters. The sensible heat transported by flue gases is evaluated as:

$$Q_{stack} = \dot{m}_{fg} * c_p * (T_{fg} - T_{amb}) \tag{4}$$

Where:
$\dot{m}_{fg}$ – flue gas mass flow rate,
c_p – constant pressure specific heat capacity,
T_{fg} – flue gas temperature,
T_{amb} – ambient temperature.

The flue gas mass flow rate is directly influenced by excess air ratio. Increasing excess air increases nitrogen dilution and raises total exhaust mass, even if combustion remains complete. Therefore, stack loss sensitivity to excess air becomes thermodynamically significant. For analytical estimation, flue gas mass flow is approximated from stoichiometric combustion relationships with correction for excess air percentage. Heat dissipated through furnace walls is approximated using steady-state heat transfer relations:

$$Q_{wall} = U * A * (T_{surf} - T_{amb}) \tag{5}$$

Where:
U – overall heat transfer coefficient across refractory and insulation layers,
A – effective casing area,
T_{surf} – wall surface temperature.

To validate the applicability of the developed analytical framework, a representative refinery furnace operating at steady load is examined. Assumed operational parameters:

- Fuel input: 12 MW
- Flue gas temperature: 900°C
- Ambient temperature: 25°C
- Average flue gas specific heat: 1.1 $kJ/kg * K$
- Wall heat transfer coefficient: 0.8 $W/m^2 * K$
- Effective casing area: $450\ m^2$

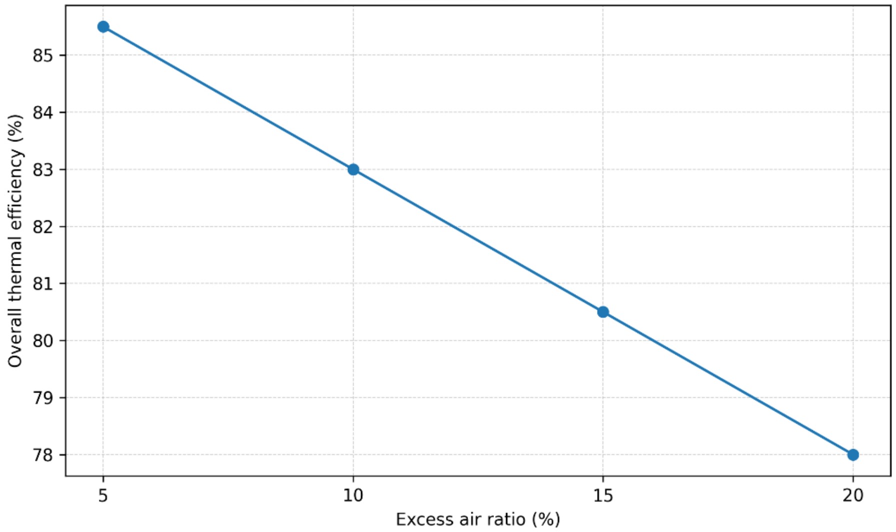
Two excess air scenarios are evaluated: 10% and 20%.

Influence of Excess Air on Stack Loss and Thermal Efficiency

Excess Air (%)	Flue Gas Flow (relative)	Stack Loss (%)	Wall Loss (%)	Overall Efficiency (%)
10	1.00	17	4	83
20	1.12	22	4	78

The results as shown in the table above indicate that increasing excess air from 10% to 20% leads to an approximate 5% reduction in thermal efficiency. This reduction is primarily attributed to increased flue gas enthalpy discharge rather than combustion improvement. Wall losses remain relatively stable under constant structural conditions, confirming that operational parameters exert stronger influence on stack-related dissipation. The parametric evaluation demonstrates that excess air control constitutes a high-impact operational variable. A 5% efficiency deviation in a 12 MW furnace corresponds to approximately 0.6 MW additional fuel demand. Over extended annual operation, such deviation translates into substantial economic and environmental consequences. The proposed heat balance framework therefore provides a technically transparent method for:

- Quantifying dominant loss contributors
- Prioritizing corrective actions
- Supporting energy audit procedures



Effect of excess air ratio on furnace thermal efficiency

Within the practical operating interval of excess air ratios (approximately 5–20%) as shown in the graph above, the relationship between excess air and thermal efficiency may be treated as quasi-linear for preliminary engineering evaluation. Although the underlying thermodynamic interactions are inherently non-linear, the combined influence of flue gas mass increase and moderate temperature variation produces an approximately proportional trend in this restricted range. Therefore, linear approximation provides sufficient accuracy for diagnostic and comparative analysis. Outside this interval, however, non-linear behavior becomes more pronounced and should be evaluated using more detailed methods.

Sensitivity analysis of key operating parameters. In addition to the base-case parametric evaluation, it is necessary to assess the sensitivity of furnace thermal efficiency to variations in key operating parameters. Sensitivity analysis enables identification of variables that exert the strongest influence on overall performance and therefore deserve priority in operational control strategies.

Stack-related losses exhibit a direct dependence on flue gas temperature. According to the heat balance formulation, sensible heat discharge increases proportionally with the temperature difference between exhaust gases and ambient conditions. For a representative 12 MW furnace, an increase in flue gas temperature from 850°C to 950°C, assuming constant mass flow rate, results in a measurable rise in stack heat loss. Even moderate temperature escalation can therefore reduce overall efficiency in a noticeable manner. This observation underlines the importance of maintaining effective heat transfer in radiant and convection sections to prevent unnecessary exhaust overheating.

Excess air ratio constitutes another highly sensitive operational parameter. Increasing excess air not only raises flue gas mass flow rate but also introduces thermal dilution effects due to additional nitrogen. While a certain margin of excess air is required to ensure complete combustion, excessive levels intensify sensible heat discharge through the stack. Within the practical operating range of 5–20%, efficiency variation may be approximated as quasi-linear for engineering estimation purposes. However, beyond this interval, non-linear behavior may become more pronounced due to stronger combustion temperature shifts and dilution effects.

Structural conditions also influence efficiency stability. An increase in wall heat transfer coefficient, caused by insulation degradation or refractory aging, leads to higher conductive and radiative losses. For example, if wall losses rise from 4% to 6% under otherwise identical firing conditions, overall efficiency decreases correspondingly. Although wall losses typically remain smaller than stack losses, their gradual growth over time can contribute to persistent efficiency deterioration.

Comparative evaluation indicates that stack-related parameters—particularly excess air ratio and exhaust temperature—exhibit greater sensitivity than structural heat losses under normal operating conditions. Consequently, operational optimization measures should be prioritized before structural modifications are considered. Systematic monitoring of oxygen concentration and flue gas temperature therefore provides the most immediate and technically feasible pathway for improving thermal performance in refinery furnace systems.

Application of the obtained results. The analytical assessment developed in this study provides a structured basis for practical performance evaluation of refinery process furnaces. By decomposing total thermal input into identifiable loss components, the proposed heat balance framework enables engineers to distinguish between operational and structural inefficiencies. From an operational perspective, the results indicate that excess air control represents a high-impact adjustment parameter. The parametric evaluation demonstrated that reducing excess air from 20% to 10% may increase thermal efficiency by approximately 5%. For a 12 MW furnace operating continuously, this improvement corresponds to nearly 0.6 MW reduction in fuel demand. Over long-term operation, such reduction translates into significant annual fuel savings and measurable emission mitigation. In addition to combustion control, the model supports diagnostic assessment of stack-related losses. Since stack gas discharge constitutes the dominant loss mechanism in the examined scenarios, monitoring flue gas temperature and oxygen concentration becomes essential for efficiency optimization. The presented framework may therefore serve as a simplified auditing tool for refinery energy management systems. The evaluation of wall heat losses further indicates that insulation integrity plays a stabilizing role in maintaining performance. Although wall losses remain comparatively smaller than stack losses under normal conditions, aging refractory materials or casing damage may progressively increase heat dissipation. The analytical relations introduced in this study allow preliminary estimation of such structural degradation effects without advanced numerical modeling.

Moreover, the developed approach can assist in preliminary feasibility assessments for waste heat recovery integration. By quantifying stack energy content, engineers may estimate recoverable heat potential prior to detailed design of economizers or air preheaters. This supports economically justified decision-making during modernization projects. Overall, the obtained results provide a technically transparent and practically applicable methodology for identifying dominant energy loss sources, prioritizing corrective actions, and supporting efficiency-oriented operational strategies in refinery furnace systems.

Conclusion. The conducted analysis demonstrated that thermal efficiency of process furnaces is governed by the combined influence of operational and structural parameters. By applying a structured heat balance framework, the study identified stack-related losses as the dominant mechanism of energy dissipation under typical refinery operating conditions. Among the examined variables, excess air ratio and flue gas temperature exhibited the highest sensitivity with respect to overall efficiency variation. The parametric evaluation showed that moderate deviations in excess air may result in measurable efficiency deterioration, primarily due to increased flue gas mass flow and sensible heat discharge. In contrast, wall heat losses, although generally smaller in magnitude, may progressively increase in the presence of insulation degradation or refractory aging. These findings emphasize the necessity of systematic monitoring of combustion conditions and structural integrity. The proposed analytical approach provides a practical and transparent methodology for preliminary efficiency diagnostics without reliance on complex numerical simulations. Its application may support operational optimization, energy auditing, and informed decision-making in refinery furnace performance management.

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