The Modern Fired Heater: A Comprehensive Guide to Optimizing Efficiency, Reliability, and Safety

Executive Summary

Fired heaters are the single largest energy consumers within a refinery or petrochemical plant, accounting for 40% to 70% of total site energy consumption.[1] Consequently, their optimization represents the most significant lever for improving site-wide energy efficiency, reducing operational expenditures, and enhancing overall profitability. While often designed for high thermal efficiency, many heaters operate well below their peak potential due to fluctuating operating conditions, fuel variability, and gradual degradation of components.[1] This report provides an exhaustive, expert-level analysis of the strategies, technologies, and best practices available to optimize fired heater performance, focusing on the dual objectives of maximizing fuel efficiency and mitigating associated operational risks.

The analysis is structured around four fundamental pillars of optimization: **Combustion Control**, **Thermal Performance Enhancement**, **Digital Transformation**, and **Reliability Management**. The strategies discussed range from foundational operational tuning with rapid returns to advanced digital solutions and capital-intensive revamps that unlock step-changes in performance and capacity. A central theme of this report is the deep interconnection between efficiency and safety; a more efficient, tightly controlled heater is invariably a safer, more reliable, and longer-lasting asset.

The economic justification for these optimization projects is compelling. Simple operational adjustments and tuning can yield energy savings of 2-4% with payback periods of less than one year.[1] More significant investments in advanced instrumentation, heat recovery systems, and digital controls demonstrate robust returns on investment, typically paying back within one to five years while delivering substantial, long-term value.[3] The case studies presented throughout this report provide quantifiable evidence of these benefits, demonstrating fuel consumption reductions exceeding 5%, capacity increases of over 15%, and run-length extensions

of several years. This report serves as a comprehensive guide for process engineers, operations managers, and plant directors to identify, justify, and implement a holistic fired heater optimization program that aligns with strategic goals for profitability, sustainability, and operational excellence.

Optimization Strategy	Primary Benefit	Typical Fuel/Energy Savings (%)	Secondary Benefits	Typical Payback Period	Key Case Study & Quantifiable Result
Advanced Damper & Register Control	Fuel Savings	1-4%	NOx Reduction, CO2 Reduction	< 1 Year	German Refinery: 3% efficiency gain via manual tuning of dampers and registers.[1]
CO-Based Trim Control	Fuel Savings	2-5%	Tighter Combustion Control, Safety	1-2 Years	Spanish Refinery: >5% fuel savings achieved by reducing average O2 from 5-7% to ~2% using a controlled-furnace approach.[5]
TDLS Installation (In-Situ)	Fuel Savings & Safety	3-5%	Real-time Control, NOx Reduction, BMS Safety Permissive (CH4)	1-3 Years	Yokogawa Case Studies: 5% fuel reduction achieved in many cases; 1-1.5% excess O2 reduction realized, enhancing efficiency

					and safety.[6]
High-Emissivity Coatings	Fuel Savings or Throughput Increase	7-11%	Lower TMTs, Reduced CO2, Extended Tube Life	1-3 Years	PTTGC Catalytic Reformer: ~11% efficiency benefit, unlocking 9.2M barrels of additional production over 8 years.[8]
Inclined Firing System (IFS)	Increased Run Length & Reliability	N/A (Enabling)	Lower TMTs, Uniform Heat Flux, Reduced Coking	Project Specific	FIS Case Study: Heater run length increased from 3 months to 18 months (a 6x improvement) by eliminating flame impingement.[9]
Flue Gas Heat Recovery (APH/Econo)	Fuel Savings	10-25%	Reduced Stack Temperature, CO2 Reduction	1-5 Years	Iranian Refinery: Efficiency increased from 63% to 89% by installing an air preheater and reducing excess air; 1-year payback.[4]
Advanced Process Control	Economic Optimization (Yield/Energy	5-8%	Process Stability, Increased	1-3 Years	US Refinery: Implemented MPC-based

(APC)	)		Throughput		APC, resulting in an 8% reduction in energy consumption and a 3% increase in throughput.[10]
Digital Twin	Predictive Maintenance & Optimization	N/A (Enabling)	Reduced Downtime, Enhanced Safety, Scenario Simulation	Project Specific	Shell: Implementation across assets saves ~$2 billion annually through reduced downtime (20%) and maintenance costs (25%).[11]

Section I: The Fired Heater: An Operational and Economic Linchpin

To effectively optimize fired heater performance, a comprehensive understanding of its fundamental design, operational principles, and heat transfer mechanisms is essential. These units are not mere furnaces; they are complex, direct-fired heat exchangers that form the heart of numerous refinery processes. Their configuration and internal dynamics dictate both their efficiency potential and their operational vulnerabilities.

1.1 Core Functions and Components

The primary function of a fired heater is to use the hot gases generated by controlled combustion to raise the temperature of a process fluid, typically a hydrocarbon stream like crude oil or naphtha, flowing through a series of tubes.[12] This heating is necessary to achieve the required temperatures for processes such as distillation, catalytic cracking, and reforming.[13] The heat is generated by burning various fuels, including natural gas, refinery off-gases, and heavy fuel oils, in specialized burners.[12]

A fired heater is an assembly of several critical components, each playing a distinct role in its operation and efficiency [12]:

- **Burners:** Devices that mix fuel and air to produce a stable, controlled flame, providing the heat input for the system. They can be located on the floor or walls and operate under natural, forced, or induced draft conditions.[14]
- **Tubes (Coils):** Hollow metal conduits through which the process fluid flows, absorbing heat from the combustion process.[12]
- **Radiant Section:** The primary combustion chamber, where tubes are exposed directly to the flame. It is lined with refractory material to withstand extreme temperatures and reflect heat towards the tubes.[14]
- **Convection Section:** Located downstream of the radiant section, this area contains banks of tubes where heat is transferred from the hot flue gases to the incoming, cooler process fluid primarily through convection.[14]
- **Shield (or Shock) Section:** Rows of bare tubes situated between the radiant and convection sections to shield the convection tubes from direct, intense radiant heat.[13]
- **Tube Supports:** High-temperature alloy structures that hold the tubes in their correct position and alignment within the firebox.[12]
- **Refractory:** Heat-resistant lining on the interior walls and floor of the heater that provides insulation, protects the outer casing, and minimizes heat loss.[12]
- **Dampers and Air Registers:** Adjustable plates or valves that control the flow of combustion air to the burners and flue gas to the stack, regulating combustion intensity and heater draft.[12]
- **Stack:** A vertical structure that safely vents the combustion byproducts (flue gas) into the atmosphere.[12]
- **Air Preheaters (APH):** Heat recovery equipment that uses hot exhaust flue gas to preheat the incoming combustion air, improving thermal efficiency.[12]
- **Fans (ID/FD):** Induced Draft (ID) fans pull flue gas out of the heater, while Forced Draft (FD) fans push combustion air into the burners. A balanced draft system uses both.[14]

1.2 Understanding Heat Transfer: The Interplay of Radiant, Convection, and Shield Zones

The overall efficiency of a fired heater is dictated by the effectiveness of heat transfer within its distinct zones, governed by the principles of radiation, convection, and conduction.[14]

The **Radiant Section** is the heart of the heater and its most critical zone for performance. Within this chamber, heat transfer is dominated by thermal radiation from the hot burner flames and incandescent refractory walls directly to the surface of the process tubes.[14] According to the Stefan-Boltzmann law, the rate of radiant heat transfer (

Qrad) is proportional to the fourth power of the absolute temperatures of the hot and cold surfaces, as shown in the equation: $Qrad=\epsilon\sigma A(Thot4-Tcold4)$.[17] This fourth-power relationship means that flame temperature and distribution are overwhelmingly the most influential factors in heater performance. Depending on the design, the radiant section is responsible for transferring between 55% and 85% of the total heat duty to the process fluid.[13] This disproportionate contribution explains why optimization strategies targeting the radiant section—such as improving burner performance, managing flame shape, and enhancing surface emissivity—yield the most significant improvements in overall fuel efficiency. A small percentage improvement in the effectiveness of radiant heat transfer has a much larger impact on the heater's fuel consumption than an equivalent percentage improvement in other sections.

The **Convection Section** serves as a vital heat recovery zone. After leaving the radiant section, the hot combustion gases (flue gas), still containing a substantial amount of thermal energy, pass over banks of tubes.[14] Here, heat is transferred primarily by convection as the hot gas flows across the tube surfaces, preheating the cooler process fluid that typically enters this section first.[14] The effectiveness of this section is crucial for maximizing the heater's overall thermal efficiency by capturing heat that would otherwise be lost up the stack.

Positioned between these two primary zones is the **Shield Section**, also known as the shock section. It consists of several rows of tubes, often bare or with limited finning, that serve a protective function.[13] Their primary role is to absorb the intense direct radiation from the firebox, shielding the more tightly packed and often finned tubes of the convection section from overheating and potential damage.[13] While they absorb some heat, their main purpose is to moderate the temperature of the flue gas before it enters the main convection bank.

1.3 Key Heater Configurations and Their Applications

Refinery heaters are designed in several standard configurations, as defined by standards like API 560, with the choice depending on the process requirements, required heat duty, plot space constraints, and maintenance considerations.[18]

- **Vertical Cylindrical Heater:** This is one of the most common and cost-effective designs, characterized by a vertical cylindrical firebox with serpentine or helical coils arranged along the walls.[18] The burner or burners are typically located at the bottom, firing upward. Their smaller footprint and efficient use of refractory-shielding tube surface make them a popular choice for utility services like reboilers, hot oil systems, and reactor feed heaters.[19]
- **Cabin (Horizontal Coils) Heater:** This design features a rectangular, cabin-like firebox with horizontal process tubes mounted along the longer walls.[18] Cabin heaters are often the preferred choice for critical, high-duty services such as crude oil and vacuum heaters.[19] The horizontal tube arrangement facilitates mechanical cleaning (decoking), which is a crucial maintenance activity for services prone to internal fouling. Furthermore, their structure is inherently more capable of supporting large convection sections, making them suitable for applications requiring high thermal efficiency and significant heat recovery.[19]
- **Box (Vertical Coils) Heater:** This configuration features a box-shaped firebox with vertical tubes, combining some benefits of the cabin and vertical cylindrical designs.[18] Like cabin heaters, they can accommodate large convection sections for high-duty services. They are often used in applications that require precise temperature control, such as in the production of specialty chemicals.[18]

In addition to the overall structure, heaters are also classified by their burner firing direction, which influences heat distribution and suitability for different processes [18]:

- **Up-firing:** Burners are at the bottom, firing upward. This is common in vertical cylindrical and box heaters and is suited for high heat flux applications.
- **Down-firing:** Burners are at the top, firing downward. This can be used for heat-sensitive materials or where height is constrained.

- **Side-firing:** Burners are mounted on the walls, perpendicular to the tube orientation. This can provide uniform temperature distribution across the tubes.

Section II: The Combustion Optimization Imperative: Mastering Air and Fuel

The combustion process is the engine of the fired heater, and its precise control is the most critical and impactful lever for optimizing efficiency, ensuring safety, and managing emissions. The goal is to achieve complete and stable combustion using the minimum amount of fuel and air necessary. This section delves into the nuances of combustion management, from the fundamental challenge of excess air control to the application of state-of-the-art analytical technologies and advanced burner designs.

2.1 The Excess Air Dilemma: Balancing Efficiency, Safety, and Emissions

In an ideal world, fuel would be burned with the exact, chemically correct amount of air required for perfect combustion, a condition known as stoichiometric combustion.[20] However, in a real-world industrial furnace, achieving the perfect mixing of massive volumes of fuel and air is impossible. To ensure that every molecule of fuel finds enough oxygen to burn completely, a certain amount of

excess air must be supplied.[21] This practice is essential to prevent the formation of unburned hydrocarbons and, more critically, carbon monoxide (CO)—a toxic gas, a safety hazard, and a form of significant energy waste.[20]

This necessity creates a fundamental operational dilemma. While some excess air is required for safety and completeness of combustion, any air supplied beyond this minimum requirement is detrimental.[21] This excess air, composed primarily of inert nitrogen, does not participate in the reaction. Instead, it is heated from ambient temperature to the high temperature of the flue gas, absorbing valuable energy that is then lost directly up the stack.[20] Excessive levels of excess air lead directly to:

- **Wasted Fuel and Lower Efficiency:** More fuel is burned simply to heat the unnecessary air, directly reducing the heater's thermal efficiency.

- **Increased Fan Power Consumption:** More air requires forced and/or induced draft fans to work harder, consuming more electricity.
- **Higher NOx Emissions:** The nitrogen in the excess air is heated to high temperatures in the presence of oxygen, promoting the formation of thermal NOx, a key pollutant.[21]

Conversely, supplying too little excess air is even more dangerous and wasteful. Incomplete combustion results in unburned fuel being lost up the stack and the formation of CO. The energy lost due to even small amounts of CO in the flue gas is five to ten times greater than the energy required to heat an equivalent amount of excess air.[20] This creates a natural tendency for operators to err on the side of caution and supply more excess air than necessary, leading to chronic inefficiency.[20]

The optimization target is therefore to operate at the "knife's edge"—the lowest possible level of excess air that still guarantees complete combustion. This optimal point is typically found to correspond to an excess oxygen (O2) level of 2-3% in the dry flue gas.[2] As a widely cited rule of thumb, every 10% reduction in excess air or every 20°C reduction in stack gas temperature results in a 1% increase in heater efficiency.[21] A more specific guideline states that every 3% reduction in excess

O2 increases heater thermal efficiency by approximately 1%.[2]

2.2 Advanced Combustion Monitoring: From O_2 Trim to Superior CO-Based Control

The ability to operate safely and efficiently at low excess air levels is entirely dependent on the quality and responsiveness of the combustion monitoring and control system.

Traditionally, heater combustion has been controlled using an **O2 Trim System**. This system uses a sensor, typically a zirconium oxide probe located in the stack or convection section outlet, to measure the percentage of residual oxygen in the flue gas. The control system then adjusts the air dampers to maintain a specific O2 setpoint. However, this method has significant limitations [20]:

- **Indirect Measurement:** O2 concentration is an *indirect* or inferred measure of combustion quality. It confirms that excess reactant is present but does not confirm that the reaction is complete.

- **Susceptibility to Air Ingress:** Air can leak into the heater through inspection ports, flanges, or cracks in the casing ("tramp air"). If this leakage occurs upstream of the O2 sensor, it will give a falsely high reading, which could lead a control system or operator to dangerously reduce the actual air supply to the burners.
- **Slow Response and Ambiguity:** Stack-mounted sensors have a significant time lag. Furthermore, the system requires frequent operator adjustments to the setpoint to account for changes in fuel composition, heater load, or ambient conditions.

A fundamentally superior approach is **CO-Based Control**. This strategy uses a fast-acting analyzer to measure carbon monoxide concentration in the flue gas, typically in parts-per-million (ppm).[20] The superiority of this method stems from a critical shift in control philosophy: it moves from managing an

inferred state (sufficient oxygen) to managing a *direct result* (completeness of combustion).

The presence of CO is an unambiguous, direct signal that combustion is becoming incomplete. As excess air is reduced, the process approaches the "stoichiometric cliff," where CO levels begin to rise sharply from a baseline near zero.[25] A control system that targets a very low CO concentration (e.g., 200 ppm) can therefore push the air-to-fuel ratio to its absolute optimum point with a high degree of confidence and safety.[25] This approach overcomes the major drawbacks of

O2 control. It is largely unaffected by tramp air (which simply dilutes the CO reading but doesn't create a false safety signal) and automatically compensates for variations in fuel quality or load without requiring operator intervention.[20] By directly controlling based on the first sign of inefficiency, CO-based systems allow refineries to safely operate at much lower excess air levels, unlocking efficiency gains that are unachievable with

O2 trim alone. This enables the documented drops in O2 levels of 3-4% and reductions in NOx of 5-6 ppm that characterize a truly optimized system.[20]

2.3 The Game Changer: In-Situ Gas Analysis with Tunable Diode Laser Spectroscopy (TDLS)

The full potential of advanced combustion control is realized with state-of-the-art analytical technology. **Tunable Diode Laser Spectroscopy (TDLS)** represents a paradigm shift in fired heater gas analysis, providing the fast, accurate, and reliable data needed for high-performance control.[6]

TDLS analyzers work by projecting a laser beam of a specific wavelength directly through the process gas stream to a detector on the opposite side. The amount of light absorbed is directly proportional to the concentration of the target gas (e.g., O2, CO, CH4).[6] This technology offers several transformative advantages over traditional extractive sampling systems:

- **In-Situ, Real-Time Measurement:** The analysis is performed directly within the firebox, typically in the radiant or crossover section.[7] This provides a near-instantaneous measurement (2-5 second update cycle) of the combustion process where it is actually happening. This eliminates the long transport delays (often over 30 seconds) and potential for sample corruption associated with extractive analyzers that pull a sample from the stack.[6]
- **Path-Averaged Reading:** The laser travels across the entire width of the furnace, providing a true average concentration reading that is far more representative of the overall combustion state than a single-point probe measurement, which can be easily misled by stratified burner conditions or localized air leaks.[7]
- **Enhanced Safety and Reliability:** TDLS analyzers are non-contact and have no moving parts, leading to very high reliability and low maintenance requirements.[6] Crucially, they can measure methane (
CH4) concentration. This capability allows for an additional layer of safety in the Burner Management System (BMS), which can use a high CH4 signal as a permissive to prevent burner light-off in a pre-existing fuel-rich, potentially explosive atmosphere.[26] This is a safety feature that traditional systems cannot provide. Furthermore, TDLS replaces high-temperature zirconium oxide probes, which are a known ignition source for leaked fuel in idle heaters.[22]

Case Study (Yokogawa): The practical benefits of TDLS are well-documented. A European refinery installed a Yokogawa TDLS system for combustion management. The operators were able to reduce the percentage of excess O2 by 1% to 1.5% compared to what was achievable using their existing stack gas analyzers, allowing the heater to run more efficiently and closer to its optimal operating point. The system's fast response time also enabled quicker detection of upset conditions, enhancing overall safety.[7] In many similar installations, Yokogawa reports that fuel reductions of 5% have been achieved.[6] A separate economic analysis calculated that for a 100,000 BPD unit, a mere 0.5% reduction in excess

O_2 (from 2.5% to 2.0%) could save approximately 240 kL of fuel and 9.6 million JPY ($~65,000 USD) annually, while reducing CO_2 emissions by 720 tons.[25]

2.4 Tackling Fuel Variability: Strategies for Managing Refinery Off-Gas and Hydrogen Blends

A significant and often underestimated challenge in refinery heater optimization is the variability of the fuel source. Refineries commonly burn a mixture of purchased natural gas and internally generated refinery off-gas.[23] The composition, and therefore the heating value (BTU content), of this off-gas can fluctuate significantly based on the crude slate being processed and the operating state of various upstream units.[23]

This variability creates a major hidden inefficiency. A control system with a fixed air-to-fuel ratio will be incorrect for most of the operating time. To avoid a dangerous, fuel-rich condition when a high-BTU gas slug comes through, operators are forced to set the combustion air rate with a large "safety margin," high enough to handle the worst-case fuel scenario.[23] This means that for the vast majority of the time, when the fuel has a lower BTU value, the heater is operating with a significant and wasteful amount of excess air. Advanced control systems that can respond to these changes in real-time directly translate into profit by safely shrinking this operational buffer. Technologies like TDLS, which measure the

result of combustion (O_2/CO levels) in real-time, allow the air supply to be adjusted dynamically to maintain optimal conditions regardless of the incoming fuel's heating value.[23] A recent study demonstrated that by using real-time analysis to optimize a three-gas fuel mixture, LPG consumption could be reduced by over 50% by tailoring the fuel supply to the specific needs of different processing units.[29]

An emerging challenge is the increasing use of **hydrogen** as a fuel source for decarbonization.[32] While beneficial for reducing carbon emissions, hydrogen firing introduces new technical considerations:

- **Higher Flame Speed:** Hydrogen's flame speed is about four times faster than that of natural gas, requiring different burner aerodynamics.
- **Higher Flame Temperature:** The adiabatic flame temperature is higher, which can increase the formation of thermal NOx if not properly managed.

- **Flame Invisibility:** Hydrogen flames are nearly invisible, necessitating new flame detection methods, such as those based on sound or specialized UV/IR sensors.

Current industry experience suggests that many conventional burners can accommodate a blend of up to 30% hydrogen in the fuel gas without major modifications, but firing 100% hydrogen requires specialized, purpose-built burner systems.[32]

2.5 Meeting Environmental Mandates: The Role of Ultra-Low NOx (ULN) Burner Technology

Driven by increasingly stringent environmental regulations, the reduction of nitrogen oxides (NOx) emissions is a primary consideration in heater operation and design.[33] Modern

Ultra-Low NOx (ULN) burners are engineered to minimize NOx formation by precisely controlling the two key factors that drive it: peak flame temperature and local oxygen concentration.[34]

Key technologies employed in ULN burners include [33]:

- **Staged Combustion:** This can be done by staging either the air or the fuel. The process creates an initial fuel-rich, oxygen-poor combustion zone where temperatures are kept lower, followed by a secondary fuel-lean zone where combustion is completed. This avoids the high peak temperatures that generate the most thermal NOx.
- **Flue Gas Recirculation (FGR):** A portion of the inert flue gas from the stack is mixed with the combustion air. This dilutes the reactants, lowering the flame temperature and oxygen concentration, thereby suppressing NOx formation.
- **Pre-mixed Combustion:** Fuel and air are thoroughly mixed before entering the combustion zone. This results in a more uniform, stable, and lower-temperature flame, which prevents the high-temperature spots responsible for significant thermal NOx production.

Advanced commercial burners, such as the John Zink ECOjet® Edge, integrate these techniques to achieve NOx emissions below 9 ppm with FGR, while also being designed to be "hydrogen-ready" for future fuel transitions.[35]

Case Study (Emerson/Rosemount): The implementation of ULN burners highlights the critical need for integrated, advanced instrumentation. A North American refinery installed new ULN burners to meet emissions regulations. However, these burners operated so lean (with very low excess air) that they were constantly on the verge of flame-out, posing a significant safety and operational risk.[36] Traditional flame detectors were too costly to implement on every burner. The refinery successfully solved this problem by installing a Rosemount 3051S advanced pressure transmitter. This device was able to detect the onset of flame instability by monitoring very high-frequency pressure fluctuations (process noise) inside the firebox. This provided operators with an early warning to take corrective action

before a full flame-out and shutdown occurred, demonstrating how advanced control hardware and sophisticated instrumentation must work in concert to enable safe and efficient operation at the limits of performance.

Section III: Enhancing Thermal Performance: Advanced Heat Transfer and Recovery

Beyond optimizing the combustion process itself, significant efficiency gains can be achieved by improving how heat is transferred to the process fluid within the heater and by recovering thermal energy that would otherwise be wasted. These strategies often involve physical modifications or revamps that enhance the fundamental thermal performance of the asset.

3.1 Internal Enhancements: High-Emissivity Coatings and Advanced Design Revamps

Improving the efficiency of the radiant section, where the majority of heat transfer occurs, offers a powerful lever for optimization.

High-Emissivity Ceramic Coatings: The rate of radiant heat transfer is directly proportional to the emissivity (ϵ) of the radiating and absorbing surfaces.[17] Standard metal tubes and refractory materials have emissivities that can degrade over time due to scaling and oxidation. Applying a specialized high-emissivity ceramic coating to the internal refractory surfaces and the external surfaces of the process tubes can significantly increase their ability to radiate and absorb heat.[8] This enhancement means that the required process heat duty can be achieved at a lower firebox temperature and thus a lower fuel firing rate, resulting in direct fuel savings. Alternatively, for a constrained heater, it can allow for increased throughput at the same firing rate.

Case Study (IGS/Cetek): A catalytic reformer unit at a PTTGC refinery in Thailand was limited by heat transfer due to heavy scale formation on its radiant tubes. An engineering study recommended the application of CETEK high-emissivity ceramic coatings to both the tubes and refractory surfaces in all four cells of the heater. After the application during a turnaround, the heater demonstrated an approximate 11% benefit in radiant heat transfer efficiency, exceeding the historical average of 7% for such projects. This performance gain was utilized to increase production, unlocking an estimated 9.2 million barrels of additional capacity and saving 68,800 tons of CO2 over an eight-year period. The project provided an exceptionally fast payback and a significant return on investment.[8]

Inclined Firing Systems (IFS): A common cause of premature tube failure, localized coking, and inefficient heat transfer is direct flame impingement, where the burner flame physically touches the process tubes, creating dangerous hot spots.[37] The patented Inclined Firing System, developed by Furnace Improvements Services (FIS), addresses this by installing the burners at a slight angle (5-7°) away from the tubes.[37] This seemingly simple modification shifts the hottest part of the flame towards the center of the firebox, away from the tube surfaces. This results in a more uniform heat flux distribution, lower and more even Tube Metal Temperatures (TMTs), reduced rates of internal coking, and significantly longer tube life and heater run lengths between shutdowns for maintenance or decoking.[37]

Split Flow Technology: For heaters that are capacity-limited by the process-side pressure drop, the patented Split Flow Technology offers a powerful debottlenecking solution. This revamp strategy involves splitting the process fluid into two parallel paths. The main stream flows through the traditional convection and radiant sections, while a second "split stream" is routed through tubes located predominantly in the convection section.[37] The two streams are then recombined at the heater outlet. This parallel arrangement significantly reduces the overall pressure drop, allowing for a capacity increase of 15-30% while maintaining or even improving thermal efficiency and keeping TMTs and radiant heat fluxes low.[37]

3.2 Flue Gas Heat Recovery: A Turnkey Opportunity for Efficiency Gains

One of the largest sources of inefficiency in older or less optimized heaters is the heat lost to the atmosphere in the hot flue gas exiting the stack. It is estimated that up to 30% of all industrial heat is lost via this route.[3] Installing equipment to recover this waste heat is a cornerstone of modern efficiency projects. The primary technologies for this purpose are [39]:

- **Air Preheaters (APH):** An APH is a heat exchanger that transfers heat from the outgoing hot flue gas to the incoming cold combustion air.[40] By preheating the air before it enters the burners, less fuel is required to raise the air-fuel mixture to its ignition temperature. This directly reduces fuel consumption and improves thermal efficiency.
- **Economizers:** Similar to an APH, an economizer is a heat exchanger in the flue gas stream, but it is used to preheat a liquid, typically boiler feedwater or sometimes the process fluid itself, before it enters the main heating section.[40]
- **Waste Heat Recovery Units (WHRUs):** This is a broader term for any system designed to capture waste heat from flue gas for a useful purpose, such as generating low- or medium-pressure steam for use elsewhere in the plant.[40]

Case Study (Iranian Refinery): The dramatic impact of heat recovery was demonstrated in a mathematical modeling study of a furnace in an Iranian refinery's atmospheric distillation unit. The baseline furnace had an efficiency of 63%. The study simulated the installation of an air preheater capable of raising the combustion air temperature to 485.6°C. This modification, combined with a reduction in excess air to an optimal 15%, was projected to increase the furnace's thermal efficiency from 63% to a remarkable 89%. The economic analysis showed that the capital investment for the APH system would have a payback period of just one year, highlighting the strong financial case for flue gas heat recovery.[4]

3.3 Material Science for Corrosive Environments: Polymer and Glass Heat Exchangers

A major limitation in traditional flue gas heat recovery is the risk of corrosion. Many refinery fuels contain sulfur, which forms sulfur dioxide (SO2) and sulfur trioxide (SO3) during combustion. If the flue gas is cooled below its "acid dew point," these compounds will combine with water vapor in the gas to form highly corrosive sulfuric acid, which can rapidly destroy conventional carbon steel heat exchangers.[3] This risk has historically forced operators to maintain stack temperatures well above the dew point, leaving a significant amount of low-grade heat unrecovered.

The development of advanced, corrosion-resistant materials has pushed this boundary, unlocking a new frontier of efficiency. These materials allow for the safe recovery of heat at much lower temperatures, closer to the ambient air temperature. Key technologies include [3]:

- **Polymer Heat Exchangers:** Constructed from advanced polymers, these heat exchangers are inherently resistant to acid corrosion. They also tend to have smoother surfaces that are less prone to fouling than metal, making them an excellent choice for recovering low-grade heat from polluted or corrosive flue gas streams.
- **Glass Heat Exchangers:** Specialized heat exchangers made from borosilicate glass are also used for their exceptional resistance to a wide range of acid gases, making them suitable for particularly aggressive flue gas environments.

The availability of these technologies means that refineries are no longer constrained by the acid dew point in the same way. They can now design heat recovery systems that cool the flue gas to much lower final temperatures, maximizing the amount of recovered energy and pushing the overall thermal efficiency of the fired heater system to its practical limit.

Section IV: The Digital Transformation of Heater Operations: APC and Digital Twins

The evolution of computing power, advanced analytics, and real-time data processing is transforming fired heater optimization from a series of periodic, static adjustments into a continuous, dynamic, and economically driven process. Technologies like Advanced Process Control (APC), Digital Twins, and Computational Fluid Dynamics (CFD) provide operators and engineers with unprecedented tools to simulate, predict, and optimize performance in real-time.

4.1 Beyond Basic Control: Implementing Advanced Process Control (APC)

While a Distributed Control System (DCS) manages the basic regulatory control loops of a heater (e.g., maintaining a temperature setpoint), **Advanced Process Control (APC)** operates at a higher level to achieve broader economic objectives.[10] APC, most commonly implemented using Model Predictive Control (MPC), is a software-based solution that uses a mathematical model of the process to predict how the heater will respond to changes in multiple variables over time.[43]

Instead of controlling single variables to fixed setpoints, an APC controller continuously adjusts multiple manipulated variables (like fuel flow, damper positions, and process feed rates across different passes) simultaneously to drive the process towards an optimal economic outcome (e.g., minimizing energy consumption per barrel of feed, maximizing the yield of a high-value product) while respecting all critical operational constraints (e.g., maximum TMTs, emissions limits, equipment capacity).[10]

The benefits of APC in refining are well-established:

- **Reduced Energy Consumption:** By continuously optimizing the air-to-fuel ratio and heat distribution, APC minimizes fuel waste.
- **Enhanced Process Stability:** APC smooths out fluctuations in key parameters like coil outlet temperature, leading to more consistent product quality and less stress on equipment.
- **Increased Throughput:** By safely pushing the heater closer to its true operational limits, APC can often increase the unit's processing capacity.

Case Study (US Refinery): A major refinery in the United States implemented an MPC-based APC system on one of its units. The project resulted in a quantifiable **8% reduction in energy consumption** and a **3% increase in overall throughput**, generating an estimated $20 million in additional annual revenue.[10] In another example, Honeywell's APC solution implemented at the Slovnaft Refinery was able to identify and capture $3,000 per day in lost profit opportunities by optimizing the plant's production strategy in real-time.[44]

4.2 The Rise of the Digital Twin: Simulating, Predicting, and Optimizing in

Real-Time

A **Digital Twin** is a virtual, dynamic representation of a physical asset—in this case, the fired heater—that is continuously updated with real-time data from sensors, operational history, and analytical models.[45] It is more than a static model; it is a living simulation that mirrors the current state and behavior of the real-world heater. This technology provides powerful capabilities across the entire operational lifecycle [11]:

- **Process Optimization:** The digital twin provides a safe, virtual environment to conduct "what-if" analyses. Operators and engineers can test different fuel types, feed rates, or control strategies to find the most efficient and profitable operating point without exposing the physical asset to risk.[45]
- **Predictive Maintenance:** By integrating real-time data on temperatures, pressures, vibrations, and flow rates, the digital twin can use machine learning algorithms to predict equipment degradation and potential failures *before* they occur. This enables a shift from reactive or schedule-based maintenance to a proactive, condition-based strategy, optimizing maintenance schedules and extending asset life.
- **Enhanced Safety and Training:** The digital twin can be used to simulate emergency scenarios, such as a tube rupture or loss of flame. This allows operators to train and practice their response to high-risk events in a safe, controlled environment, improving their readiness and the effectiveness of safety protocols.[45]

Case Study (Shell): The impact of digital twin technology at scale is profound. Shell has widely implemented digital twin and artificial intelligence systems across its global assets. The company reports that this initiative saves an estimated **$2 billion annually** through benefits like a 20% reduction in equipment downtime and a 25% decrease in maintenance costs.[11] In another specific application, the consulting firm KBC described a case where a refinery successfully used a digital twin to model and mitigate a complex corrosion issue in its crude distillation unit overhead system, demonstrating the technology's power for reliability management.[46]

4.3 Leveraging Computational Fluid Dynamics (CFD) for Design and Troubleshooting

Computational Fluid Dynamics (CFD) is a powerful engineering simulation tool that provides a detailed, three-dimensional view of the complex processes occurring inside a fired heater.[9] By solving the fundamental equations of fluid flow (Navier-Stokes), heat transfer, and chemical reactions, CFD can accurately model flue gas flow patterns, temperature distribution, heat flux profiles on tube surfaces, and combustion characteristics.[47]

CFD is not a real-time control tool like APC, but rather a virtual "test bench" used for two primary purposes:

1. **Troubleshooting and Root Cause Analysis:** When a heater is experiencing problems like persistent tube hot spots, high emissions, or poor efficiency, CFD can be used to "look inside" the firebox and identify the root cause, such as poor air distribution, direct flame impingement, or inefficient flue gas recirculation patterns.[38]
2. **Design Validation and Revamp Engineering:** Before investing significant capital in a heater modification—such as installing new burners, redesigning an air plenum, or implementing a technology like Inclined Firing—CFD simulations can be used to test the proposed design virtually. This allows engineers to verify that the modification will deliver the expected performance improvements and to optimize the design before any steel is cut.[9]

Case Study (FIS): A refinery in Texas was forced to shut down an atmospheric charge heater every three months due to severe high tube metal temperatures. Furnace Improvements Services (FIS) was brought in to diagnose the problem. A detailed CFD model of the heater revealed that the existing large burners were creating very long flames and detrimental flue gas recirculation patterns that caused the overheating. FIS then used CFD to evaluate a proposed new layout with a larger number of smaller-capacity burners. The simulations confirmed that this new design would result in shorter flames, more uniform heat flux, and the elimination of the hot spots. The refinery implemented the recommendation, and the heater's run length was successfully extended from a mere **3 months to 18 months**—a six-fold improvement in reliability and availability, driven by insights gained from CFD analysis.[9] Another CFD study of an olefin plant furnace highlighted the critical importance of small holes on the burner body for ensuring proper fuel-air mixing; simulations showed that when these holes were hypothetically clogged, combustion was delayed and overall furnace temperature dropped, confirming their essential role in burner design and maintenance.[48]

Section V: Foundational Pillars of Performance: Proactive Maintenance and Risk Mitigation

Advanced optimization strategies and digital technologies can only deliver sustained value when built upon a foundation of robust equipment reliability and rigorous safety protocols. A heater that is poorly maintained or operated outside of safe limits will inevitably suffer from performance degradation, unplanned downtime, and an increased risk of catastrophic failure. Proactive maintenance and a deeply embedded safety culture are therefore not separate from optimization but are essential prerequisites for it.

5.1 Online Health Monitoring and Integrity Operating Windows (IOWs)

Effective heater management requires moving from a reactive to a proactive stance, which begins with continuous online monitoring of the asset's health. Key techniques include [49]:

- **Infrared (IR) Thermography:** This is the most critical tool for online monitoring of tube health. Using handheld pyrometers or thermal imaging cameras, operators and inspectors can regularly scan the radiant tubes through viewports to measure their surface temperature. This allows for the early detection of "hot spots," which are localized areas of overheating that can be caused by internal fouling (coke), scale buildup, or direct flame impingement. Identifying these hot spots before they lead to tube bulging or rupture is essential for preventing failures.
- **Continuous Data Analysis:** The plant's DCS should be used to continuously monitor and trend other key parameters, such as flue gas conditions (temperature, O_2, CO), combustion emissions, and process fluid temperatures and pressures.

This data becomes most powerful when used to define and enforce **Integrity Operating Windows (IOWs)**, a concept formalized in API RP 584.[49] An IOW is a pre-defined set of limits for critical process variables (e.g., maximum allowable tube metal temperature, minimum process flow rate) within which the equipment can be operated without causing unacceptable degradation. Operating outside these windows can lead to accelerated damage and a shortened asset life. By establishing and monitoring IOWs, the plant shifts its focus from simply controlling the process to actively preserving the integrity of the equipment.

5.2 Offline Inspection and Condition Assessment

While online monitoring provides a real-time health check, a comprehensive understanding of the heater's condition requires detailed offline inspections during planned turnarounds, which typically occur every 4 to 7 years.[49] These inspections are critical for quantifying damage that has accumulated over the operating cycle and for making informed repair or replacement decisions.

Standard offline inspection methods include [51]:

- **Detailed Visual Inspection:** Once the heater is cooled and accessible, inspectors visually check all components for signs of damage, such as tube bulging, sagging, or bowing; refractory cracking or spalling; and distortion of tube supports.
- **Ultrasonic Thickness (UT) Measurements:** UT instruments are used to measure the remaining wall thickness of tubes and headers to quantify metal loss from corrosion or erosion.
- **Creep Damage Assessment:** For tubes operating at high temperatures, creep is a primary life-limiting damage mechanism. This is assessed by meticulously measuring the tube diameter to detect any permanent growth or "bulging" that indicates creep strain.
- **Advanced Non-Destructive Testing (NDT):** Other techniques like in-situ metallography (replicas), magnetoscopy (to detect carburization), and radiography can be used to assess metallurgical degradation.

A transformative technology in this area is **Ultrasonic Smart Pigging**. For heaters with serpentine coils, a "smart pig"—a device equipped with an array of ultrasonic transducers—can be propelled through the entire length of a coil with water.[49] This provides a rapid, comprehensive, and high-resolution map of the tube's internal condition, including wall thickness and internal diameter, without requiring personnel to enter the hazardous firebox environment or dismantle the coil by cutting return bends.[49]

The integration of online and offline data creates a powerful reliability feedback loop.

For example, online IR thermography might identify a tube that is consistently running hotter than its neighbors. This tube is then flagged for priority inspection during the next turnaround. An offline smart pig inspection can then provide precise data on the extent of wall loss or creep damage in that specific tube. This quantitative data is then fed into a Fitness-for-Service (FFS) assessment (per API 579-1/ASME FFS-1) to calculate the tube's remaining safe life and to establish a new, more stringent IOW for its maximum operating temperature in the DCS. This cycle of monitoring, inspecting, assessing, and adjusting ensures that the heater is operated reliably for its maximum possible lifespan.

5.3 Soot Blower Optimization: A Case for Intelligent Cleaning

In heaters that fire liquid fuels or are otherwise prone to soot and ash deposition, soot blowers are used to clean the external surfaces of the convection section tubes.[24] These devices use high-pressure steam or air to dislodge deposits that would otherwise insulate the tubes and impede heat transfer.

Traditionally, soot blowing has been performed on a fixed schedule (e.g., once per shift), regardless of the actual cleanliness of the tubes.[52] This approach is inherently wasteful, as it consumes significant quantities of valuable high-pressure steam and can cause long-term erosion damage to the tubes if performed excessively.[24]

The modern approach is **Intelligent Sootblowing**. These advanced control systems monitor key heat transfer performance indicators across different parts of the convection section, such as the temperature drop of the flue gas or the pressure drop across tube banks. The system then activates specific soot blowers only when and where the data indicates that cleaning is actually needed.[24] This "as-needed" approach ensures that heat transfer is maintained while minimizing steam consumption and tube erosion.

Case Study (Jindal Power): A coal-fired power plant provides a compelling example of the benefits. The plant shifted from a fixed schedule of operating all 56 furnace wall blowers once every 8 hours to an optimized, knowledge-based schedule determined by monitoring boiler parameters. The new strategy involved blowing only a fraction of the soot blowers on a daily or every-other-day basis. This simple change in operating philosophy resulted in an annual saving of over **1,300 tons of steam**, with a corresponding reduction in fuel and water costs and an improvement in overall boiler performance.[52]

5.4 Engineering for Safety: API Standards and Safety Instrumented Systems (SIS)

A commitment to safety is the ultimate foundation of reliable and efficient operation. The refining industry relies on a framework of standards and technologies to manage the inherent hazards of fired heater operation.

API Standards: The American Petroleum Institute (API) publishes a suite of standards and recommended practices that represent the collective wisdom and best practices of the industry. For fired heaters, the most critical documents are:

- **API 560, *Fired Heaters for General Refinery Service*:** This is the cornerstone standard that provides comprehensive guidelines for the design, materials, construction, and operation of refinery heaters.[15] Adherence to API 560 is essential for ensuring a heater is fundamentally safe and reliable.
- **API RP 573, *Inspection of Fired Boilers and Heaters*:** This recommended practice provides detailed guidance on the inspection methodologies and frequencies discussed in the previous sections.[49]
- **API RP 556, *Instrumentation, Control, and Protective Systems for Fired Heaters*:** This document provides guidance on the necessary control and safety systems, and specifically recommends the use of a Safety Instrumented System (SIS) for protective actions.[22]

Safety Instrumented Systems (SIS): An SIS is a separate, independent layer of protection designed to automatically take the heater to a safe state in the event of a dangerous condition that is not handled by the basic process control system.[22] Designed and managed according to the global standard IEC 61511, an SIS continuously monitors critical parameters such as fuel gas pressure, process fluid flow, and flame presence.[22] If a dangerous deviation is detected (e.g., low process flow which could lead to tube overheating and rupture, or loss of flame which could lead to an accumulation of unburned fuel), the SIS will execute a pre-programmed logic, such as tripping the main fuel valve, to prevent a catastrophic event. The SIS is the last line of automated defense, ensuring that the heater is shut down safely when critical limits are breached.

Section VI: Strategic Synthesis and Actionable Recommendations

Optimizing a refinery's fired heaters is not a single project but a continuous improvement journey that integrates strategies across technology, operations, and maintenance. The greatest and most sustainable benefits are realized not by focusing on one solution in isolation, but by developing a holistic framework that addresses all aspects of heater performance. This concluding section synthesizes the findings of this report into a cohesive strategy and provides a practical, actionable roadmap for implementation.

6.1 A Holistic Framework for Heater Optimization

The four pillars of optimization—**Combustion**, **Thermal Performance**, **Digitalization**, and **Reliability**—are deeply interconnected. Maximum value is unlocked when improvements in one area enable and enhance performance in another. Consider the synergy of an integrated approach:

An **Advanced Process Control (APC)** system (Digitalization) can continuously optimize the economic output of the heater. However, its effectiveness is fundamentally limited by the quality of the data it receives and the responsiveness of the equipment it controls. When this APC system is fed fast, accurate, and reliable in-situ combustion data from a **TDLS analyzer** (Combustion), it can make far more precise and aggressive control moves. If the system is controlling a modern **ULN burner** (Combustion) that is capable of stable operation at very low excess air, the optimization envelope expands significantly. If this advanced control system is operating a heater that has been revamped with **high-emissivity coatings** (Thermal Performance), the baseline efficiency is already higher, allowing the APC to optimize from a more advantageous starting point. Finally, if this entire system is underpinned by a robust **Reliability Management** program that uses IOWs and advanced inspections to ensure the heater can safely handle being pushed to its limits, the full economic potential of the asset can be realized. This integrated system is far more valuable than the sum of its individual parts.

6.2 Tiered Implementation Roadmap

Recognizing that refineries have varying budgets, turnaround schedules, and technical priorities, a phased implementation approach is most practical. The following tiered roadmap provides a logical progression from foundational, low-cost improvements to advanced, strategic investments.

Tier 1: Foundational Improvements (Low/No CAPEX, <1 Year Payback)
This tier focuses on leveraging existing assets and personnel to capture the "low-hanging fruit" of efficiency gains.

- **Action:** Conduct a comprehensive energy audit and operational assessment of all critical heaters to establish a detailed performance baseline and identify key areas for improvement.[39]
- **Action:** Implement a program of rigorous manual operational tuning. This involves training operators on combustion principles and empowering them to make regular, data-driven adjustments to stack dampers and burner air registers to maintain optimal draft and excess O2 levels.[20]
  - **Justification:** A case study at a German refinery demonstrated a **3% thermal efficiency gain** from these simple adjustments alone, with a payback period of less than one year.[1]
- **Action:** Review and strengthen the existing maintenance and inspection procedures for refractory, tube supports, and burner cleanliness.

Tier 2: Intermediate Investments (Medium CAPEX, 1-5 Year Payback)
This tier involves targeted capital projects, often executable during planned turnarounds, that upgrade key components and systems for a step-change in performance.

- **Action:** Upgrade combustion analysis instrumentation by replacing outdated stack-mounted O2 probes with modern in-situ **TDLS analyzers** for O2 and CO measurement.[6]
  - **Justification:** This enables tighter, safer combustion control, with documented fuel savings of up to **5%** and typical payback periods of 1-3 years.[6]
- **Action:** Install **flue gas heat recovery systems**, such as air preheaters or economizers, on high-duty heaters with high stack temperatures.[3]
  - **Justification:** This is one of the most impactful efficiency projects, with potential efficiency gains of over **20 percentage points** and payback periods of 1-5 years, as shown in the Iranian refinery case study.[4]
- **Action:** Apply **high-emissivity ceramic coatings** to the radiant section tubes and refractory during the next major turnaround.

    - **Justification:** This can yield an efficiency benefit of **7-11%**, directly translating to fuel savings or increased throughput, with a typical payback of 1-3 years.[8]
- **Action:** Implement a pilot **APC/MPC** project on a single, high-value heater to prove the technology and build internal expertise.
    - **Justification:** Documented energy savings of **5-8%** provide a strong financial case for this technology.[10]

Tier 3: Advanced Strategies (High CAPEX, Strategic ROI)
This tier represents major strategic investments that fundamentally transform the heater's capability and integrate it into a plant-wide optimization strategy.

- **Action:** Implement a **Digital Twin** for critical heaters, integrating real-time data for predictive maintenance, operator training, and "what-if" optimization simulations.
    - **Justification:** While a high-investment project, the value from dramatically reduced unplanned downtime (up to 20%) and optimized maintenance can be immense, as demonstrated by Shell's $2 billion in annual savings.[11]
- **Action:** Execute major heater revamps, such as **Inclined Firing Systems** or **Split Flow Technology**, to resolve fundamental design limitations like flame impingement or pressure drop, thereby increasing run length and capacity.[37]
- **Action:** Expand APC from a unit-level controller to a **plant-wide real-time optimizer** that coordinates multiple units for maximum site profitability.[44]
- **Action:** Prepare for the energy transition by investing in **hydrogen-ready burners** and fuel systems for key heaters, future-proofing the assets against evolving fuel markets and emissions regulations.[32]

6.3 Building the Business Case: Quantifying ROI and Long-Term Value

A successful optimization program requires a compelling business case that clearly articulates the total value proposition to senior management. The financial justification should extend beyond simple fuel savings to encompass the full spectrum of economic benefits. The business case should quantify:

1. **Direct Cost Savings:** This is the most straightforward calculation, based on the projected percentage reduction in fuel consumption multiplied by the annual fuel cost for the heater.
2. **Value-Added Benefits (Increased Revenue):** For debottlenecking projects (e.g.,

Split Flow, high-emissivity coatings), the value of the increased throughput or yield of high-value products should be calculated based on current market prices. This often represents the largest financial gain.

3. **Emissions Reduction Value:** The reduction in CO2 and other regulated emissions should be quantified. This value can be monetized based on applicable carbon taxes, the cost of purchasing emissions credits, or the avoidance of regulatory penalties.
4. **Risk-Adjusted Value (Cost Avoidance):** This critical component captures the value of improved reliability and safety. It should include:
    - The cost of **avoided unplanned shutdowns**, calculated as the value of lost production for the duration of the outage.
    - The cost of **avoided maintenance and repairs**, such as the significant expense of an emergency tube replacement.
    - The value of **extended asset life** and longer, more predictable run-lengths between major turnarounds, which defers future capital expenditure and increases overall plant availability.

In the modern refining landscape, characterized by volatile margins, stringent environmental pressures, and intense competition, the optimization of fired heater performance is not merely an option for incremental cost savings. It is a strategic imperative for ensuring long-term profitability, operational resilience, and a sustainable license to operate.

Works cited

1. New Approach to Optimizing Fired Heaters - Energy Systems ..., accessed June 23, 2025, http://ietc.tamu.edu/wp-content/themes/IETC2016/docs/2010/IETC2010Proceedings.pdf
2. Saving energy and improving process performance for fired heaters, accessed June 23, 2025, https://www.valmet.com/insights/articles/flow-control/saving-energy-and-improving-process-performance-with-flow-control-solutions-for-fired-heaters/
3. Heat recovery - Heat Matrix, accessed June 23, 2025, https://www.heatmatrix.nl/en/industrial-heat-recovery/
4. Improving of Refinery Furnaces Efficiency Using Mathematical ..., accessed June 23, 2025, https://www.researchgate.net/publication/271296682_Improving_of_Refinery_Furnaces_Efficiency_Using_Mathematical_Modeling
5. Improve efficiency of furnaces and boilers - Inercomunicación, accessed June 23, 2025, https://inercomunicacion.com/en/improve-efficiency-of-furnaces-and-boilers/

6. Achieve Optimal Combustion of Fired Heater Using TDLS to Reduce Environmental Impacts and Increase Manufacturing Efficiency - Yokogawa, accessed June 23, 2025, https://www.yokogawa.com/library/resources/application-notes/achieve-optimal-combustion-of-fired-heater-using-tdls-to-reduce-environmental-impacts-and-increase-manufacturing-efficiency/
7. Tunable Diode Laser Gas Analysis for Combustion Management in ..., accessed June 23, 2025, https://blog.yokogawa.com/blog/tunable-diode-laser-analysis-for-combustion-management-in-fired-heaters-controlled-combustion
8. Boosting Refinery Output: How Enhanced Fired Heater Efficiency Unlocked Millions of Barrels in Additional Capacity - Integrated Global Services, accessed June 23, 2025, https://integratedglobal.com/case_studies/improving-fired-heater-performance-reliability/
9. CFD SIMULATIONS TO IMPROVE THE PERFORMANCE OF FIRED ..., accessed June 23, 2025, https://ashutosh-garg.squarespace.com/s/FIS-CFD-Case-study-073119.pdf
10. Advanced Process Control (APC): The Secret Weapon of the ..., accessed June 23, 2025, https://zeroinstrument.com/advanced-process-control-apc-the-secret-weapon-of-the-refining-industry-and-its-potential-beyond/
11. Digital Twins in Oil & Gas: Real Results from Top Energy ..., accessed June 23, 2025, https://energiesmedia.com/digital-twins-in-oil-gas-real-results-from-top-energy-companies/
12. What Is a Fired Heater? Key Functions and Benefits Explained, accessed June 23, 2025, https://www.petrosync.com/blog/what-is-fired-heaters/
13. Process Heaters, Furnaces and Fired Heaters - Continental Process Instruments, accessed June 23, 2025, https://cpinstruments.com/wp-content/uploads/2020/02/o-g-oxigeno-en-calentadores-y-hornos.pdf
14. Analysis Of Fired Heaters Components | Raadman, accessed June 23, 2025, https://raadmanburner.com/blog/fired-heater/
15. API 560 Explained: Essential Guide to Fired Heater Inspections, accessed June 23, 2025, https://www.petrosync.com/blog/what-is-api-560/
16. Conductive Heat Transfer in Fired Heaters - HeaterSIM, accessed June 23, 2025, https://www.heatersim.com/knowledge/ReadArticle?Conductive-Heat-Transfer-in-Fired-Heaters-Article-2652023_175857_28234
17. Relevant Heat Transfer Correlations in Fired Heaters - HeaterSIM, accessed June 23, 2025, https://www.heatersim.com/knowledge/ReadArticle?Relevant-Heat-Transfer-Correlations-in-Fired-Heaters-Article-652024_231747_75904
18. Exploring Various Types of API Heaters - HeaterSIM, accessed June 23, 2025, https://www.heatersim.com/knowledge/ReadArticle?Exploring-Various-Types-of-

API-Heaters-Article-1142024_143326_56735
19. API 560 Fired Heater Design and Layout - HeaterSIM, accessed June 23, 2025, https://www.heatersim.com/knowledge/heater_configurations
20. Excess Air Control For Energy Efficiency - Control Engineering, accessed June 23, 2025, https://www.controleng.com/excess-air-control-for-energy-efficiency/
21. Improving of Refinery Furnaces Efficiency Using Mathematical Modeling, accessed June 23, 2025, https://www.ijmo.org/papers/14-P30023.pdf
22. Safety System Considerations for Process Fired Heaters, accessed June 23, 2025, https://www.emersonautomationexperts.com/2013/industry/downstream-hydrocarbons/safety-system-considerations-for-process-fired-heaters/
23. Fired Heaters in the Process Industries - Yokogawa, accessed June 23, 2025, https://web-material3.yokogawa.com/13/34234/files/CombustionOne_WhitePaper_v1.pdf
24. B&W Learning Center Articles » Babcock & Wilcox, accessed June 23, 2025, https://www.babcock.com/home/about/resources/learning-center/boiler-operations-that-affect-efficiency-part-2
25. Optimum Combustion Control by TDLS200 Tunable Diode Laser ..., accessed June 23, 2025, https://www.yokogawa.com/us/library/resources/yokogawa-technical-reports/optimum-combustion-control-by-tdls200-tunable-diode-laser-gas-analyzer/
26. Up Your Fired Heater Safety with TDLS Technology | Yokogawa ..., accessed June 23, 2025, https://www.yokogawa.com/us/library/resources/media-publications/up-your-fired-heater-safety-with-tdls-technology/
27. #Yokogawa #Tunable Diode #Laser Spectrometer #TDLS8000 Introduction Video #Analyzerinstruments - YouTube, accessed June 23, 2025, https://www.youtube.com/watch?v=umkW8NMo3bo
28. Achieve Optimal Combustion of Fired Heater Using TDLS to Reduce Environmental Impacts and Increase Manufacturing Efficiency - Yokogawa, accessed June 23, 2025, https://www.yokogawa.com/us/library/resources/application-notes/achieve-optimal-combustion-of-fired-heater-using-tdls-to-reduce-environmental-impacts-and-increase-manufacturing-efficiency/
29. (PDF) Fired Heaters Optimization by Estimating Real-Time ..., accessed June 23, 2025, https://www.researchgate.net/publication/386586531_Fired_Heaters_Optimization_by_Estimating_Real-Time_Combustion_Products_Using_Numerical_Methods
30. Fired Heaters in the Process Industries - Yokogawa, accessed June 23, 2025, https://web-material3.yokogawa.com/2/29493/files/CombustionOne%20White%20Paper%20v1.pdf
31. Fired Heaters Optimization by Estimating Real-Time Combustion ..., accessed June 23, 2025, https://www.mdpi.com/1996-1073/17/23/6190
32. Future-ready heaters | Wood, accessed June 23, 2025, https://www.woodplc.com/solutions/expertise/future-ready-heaters
33. Ultra Low NOx Burner Testing | Rogue Combustion, accessed June 23, 2025,

https://www.roguecombustion.com/ultra-low-nox-burner-testing
34. NOx Reduction Technologies In Industrial Burners | Raadman, accessed June 23, 2025, https://raadmanburner.com/blog/nox-reduction-in-burners/
35. ECOjet® Edge Ultra-Low NOx Burner | John Zink, accessed June 23, 2025, https://www.johnzink.com/products/boiler-burners/ecojet-edge
36. Refinery Reduced Risk of Shutdowns and Improved Plant ... - Emerson, accessed June 23, 2025, https://www.emerson.com/documents/automation/case-study-refinery-reduced-risk-of-shutdowns-improved-plant-safety-advanced-diagnostics-capability-rosemount-en-74196.pdf
37. Uniform Heat Transfer In Fired Heaters - Furnace Improvements, accessed June 23, 2025, https://ashutosh-garg.squarespace.com/s/Company-Profile-FIS.pdf
38. Improving Fired Heater Performance Using CFD: Case Study 1 ..., accessed June 23, 2025, https://www.scribd.com/document/497826756/case1
39. How to optimize energy consumption in refinery heaters, accessed June 23, 2025, https://eureka.patsnap.com/article/how-to-optimize-energy-consumption-in-refinery-heaters
40. Optimizing Fired Heater Energy Efficiency - HeaterSIM, accessed June 23, 2025, https://heatersim.com/knowledge/ReadArticle?Optimizing-Fired-Heater-Energy-Efficiency-Article-2652023_163436_50981
41. Target Markets For Flue Gas Waste Heat Recovery - News, accessed June 23, 2025, https://www.vrcoolertech.com/news/target-markets-for-flue-gas-waste-heat-recover-84979415.html
42. Flue gas treatment as a means of industrial heat recovery, accessed June 23, 2025, https://www.alliance-allice.com/en/flue-gas-treatment-as-a-means-of-industrial-heat-recovery
43. Advanced Process Control: Definition, Benefits, and Applications ..., accessed June 23, 2025, https://cruxocm.com/advanced-process-control/
44. Advanced Process Control - Honeywell Process Solutions, accessed June 23, 2025, https://process.honeywell.com/us/en/products/industrial-software/process-optimization/advanced-process-control
45. What is digital twin technology in refineries? - Patsnap Eureka, accessed June 23, 2025, https://eureka.patsnap.com/article/what-is-digital-twin-technology-in-refineries
46. Revolutionizing Refining with Digital Twins | KBC, accessed June 23, 2025, https://www.kbc.global/resources/whitepapers/revolutionizing-refining-with-digital-twins/
47. CFD Modeling | Enhance Heater Efficiency Today — Furnace ..., accessed June 23, 2025, https://www.heatflux.com/cfd-modeling
48. Analyzing Burner Performance and Combustion Phenomenon in an ..., accessed June 23, 2025, https://pubs.acs.org/doi/10.1021/acsomega.4c00395

49. Fired Heater Health Monitoring and Reliability ... - Quest Integrity, accessed June 23, 2025, https://www.questintegrity.com/wp-content/uploads/2023/04/eBook-Fired-Heater-Health-Monitoring-and-Reliability-Management.pdf
50. Evaluation of Refinery Process Heaters - Arveng Training ..., accessed June 23, 2025, https://arvengtraining.com/en/evaluation-of-refinery-process-heaters/
51. Fired Heater Inspection Manual PDF | PDF | Pipe (Fluid Conveyance ..., accessed June 23, 2025, https://www.scribd.com/document/453000903/Fired-Heater-Inspection-Manual-pdf
52. Soot Blowing Optimization- Field Experience | PDF - SlideShare, accessed June 23, 2025, https://www.slideshare.net/slideshow/soot-blowing-optimization-field-experience/46631751
53. Fired Heater Safety II - HeaterSIM, accessed June 23, 2025, https://www.heatersim.com/knowledge/ReadArticle?Fired-Heater-Safety-II-Article-1042024_52845_49731
54. API 560 - Fired Heaters for General Refinery Service ..., accessed June 23, 2025, https://inspectioneering.com/tag/api+560