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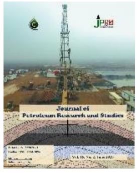

Ceramic Fiber and Refractory Castable Linings in a Refinery Furnace: A Case Report from Haditha Refinery

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Abstract

Most refinery furnaces have a metal shell around the entire assembly with a backup layer in the linings to protect the working lining from extreme conditions. Conventional thermal insulation approaches in small refinery furnace units have used refractory castable, while ceramic fibers offer different thermal properties, but this installation does not allow direct material comparison. This paper presents a case report of a 2023 crude oil heating furnace installed at Haditha Refinery, where ceramic fibers were used in the radiation zone (≈ 800 °C, 103 m^2) and refractory castable in the convection zones (≈ 450 °C, 250 m^2). Because the two zones differ in temperature, heat transfer mechanism, and mechanical stress, this study does not provide a direct material comparison. Steady-state thermal modeling gave an estimated heat flux of ≈ 1850 W/m^2 for ceramic fiber under its actual operating conditions, and ≈ 3120 W/m^2 for refractory castable under its own conditions. Theoretical heat flux estimates are reported, but no direct material comparison is possible due to different operating conditions. No operational fuel consumption or external temperature measurements were collected. All heat loss and fuel consumption estimates presented in this paper are theoretical, based on steady-state conduction modeling using manufacturer-supplied thermal conductivity values. No validated fuel savings percentage is reported.

Keywords: Refractory Castable; Ceramic Fibers; Furnace Lining; Case Report; Haditha Refinery; Thermal Simulation.

استخدام بطانات الألياف السيراميكية والخرسانة الحرارية في أفران التكرير – دراسة حالة من مصفاة حديثة (العراق)

الخلاصة:

تزود معظم أفران التكرير بغلاف معدني يحيط بالهيكل بأكمله، مع طبقة خلفية في البطانات لحماية البطانة العاملة من الظروف القاسية اعتمدت طرق العزل الحراري التقليدية في وحدات الأفران صغيرة الحجم على الخرسانات الحرارية المقاومة للصهر، في حين توفّر الألياف الخزفية خواصاً حرارية مختلفة، إلا أن هذا التركيب لا يسمح بإجراء مقارنة مباشرة بين المواد. تعرض هذه دراسة حالة لفرن تسخين النفط الخام عام 2023 في مصفى حديثة، حيث تم استخدام الألياف الخزفية في منطقة الإشعاع (حوالي 800 درجة مئوية، بمساحة 103 م^2) والخرسانة المقاومة للصهر في مناطق الحمل الحراري (حوالي 450 درجة مئوية، بمساحة 250 م^2). ونظراً لاختلاف المنطقتين في درجة الحرارة، وآلية انتقال الحرارة، والإجهاد الميكانيكي، فإن هذه الدراسة لا تقدّم مقارنة مباشرة بين المواد. أسفرت النمذجة الحرارية في الحالة المستقرة عن تقدير كثافة التدفق الحراري بحوالي 1850 واط/م^2 للألياف الخزفية تحت ظروف تشغيلها الفعلية، وحوالي 3120 واط/م^2 للخرسانة المقاومة للصهر تحت ظروفها الخاصة. تم عرض تقديرات نظرية لكثافة التدفق الحراري، غير أنه لا يمكن إجراء مقارنة مباشرة بين المواد نظراً لاختلاف ظروف التشغيل. لم يتم جمع بيانات فعلية عن استهلاك الوقود أو قياسات لدرجات الحرارة السطحية الخارجية. جميع تقديرات فقدان الحرارة واستهلاك الوقود المعروضة في هذه الورقة هي تقديرات نظرية، تستند إلى نمذجة التوصيل الحراري في الحالة المستقرة باستخدام قيم التوصيل الحراري المقدمة من قبل الشركة المصنعة. ولم تسجل اي نسبة مئوية متحققة عمليا لتوفير الوقود.

1. Introduction

1.1. Background

The furnace is an equipment to use for melting the metals for casting or heating of material for changing shape and size like rolling, forging etc. It is also used for the alteration of the properties of metals like heat treatment methods. Furnaces are usually categorized into two categories based on method of producing heat; it is combustion-type as well as electric type. Cleaning of combustion type furnace: Oil and coal are typically used as fuel in combustion-type furnaces. Electric type furnace named as induction furnace. These are mainly employed within vehicle and melting scrap market segments. For very simple heat transfer problems involving simple geometries with simple boundary conditions, analytical methods are well suited but when the respective problem becomes more complex and multiple physics want to govern than it is hardly an analytical solution. The numerical formulation and mathematical modeling of heat transfer problem have various methods like finite difference method, finite element method and boundary element method etc. This is the reasonable problem that we have conducted extensive literature studying on**.** Small refineries in Iraq (Amarah, Samawah, Najaf, Diwaniyah, Sinnya, Kask, Haditha) are typically mobile topping units of ~10,000 barrels/day, introduced from the 1940s onward, with Haditha among the earliest [1]. These refineries produce naphtha, gas oil, and residual oil. Furnaces heat crude oil to ~350 °C prior to distillation, requiring effective thermal insulation. Conventional refractories (castables, bricks) provide mechanical strength but have high density and thermal mass, leading to slower heating/cooling and increased energy consumption. Ceramic fibers are lighter, have lower thermal conductivity, better thermal shock resistance, and lower thermal mass, enabling faster cycles and reduced structural stress [2]. However, these materials were applied in different zones of the Haditha furnace under different operating conditions. Therefore, this work is presented as a case report, not a comparative study.

1.2. Literature Review

Some previous research conducted in industrial furnaces has compared the different behaviours of ceramic fiber and refractory castable linings. In a research program where individually layered ceramic fiber, ceramic fiber veneer, and hard refractory were placed into the same furnace and retested, Cameron Iron Works [3], for example, reported 40% and 31% savings in fuel. Fundamental comparisons of lining materials have shown that ceramic fiber provides lower thermal conductivity and thermal mass; however, it exhibits lower mechanical strength and abrasion resistance [4]. Thermal performance evaluations of ceramic fiber linings have demonstrated a significant reduction in heat loss compared with dense castable materials [5]. However, most comparative studies use controlled laboratory setups or identical furnace zones. There is a lack of documented real-world installations where the two materials are applied in different zones of the same refinery furnace. This case report addresses that gap by documenting the Haditha installation without claiming direct material comparison. Most of the comparative studies available on the explanations process are still reliant on either controlled laboratory configuration or on similar furnace zones. This case report addresses that gap by documenting the Haditha installation without claiming direct material comparison. The refractor serves as thermal insulation with low thermal technical conductivity (which is the thermal technical conductivity observed with use of materials with a low thermal technical conductivity and a thick lining) with low transfer of heat to the environment. The furnace shell remains protected, heat losses to the environment are low so heat is retained within the vessel and thus the process temperature is preserved [6]. A refractory castable, refers to the free, physical and physically, and chemical bound water. Explosive spalling was attributed by studies [7] to the failure to prevent loss of water through the thick refractory surface as heating occurs, therefore rapidly creating a high-water vapor pressure. Firstly, with the increase in temperature, free water evaporates at around 100 ºC, and water that is bound physically can be evaporated up to 200 ºC [8]. On the other hand, bound water escapes from the breakdown of hydrates of calcium aluminate cement until 400 ºC [9]. Water vapor that is physically and chemically bound migrates towards the heated surface, or condenses in the cooler sections of the material, creating a saturated layer that prevents deeper migration inwards. With further heating, more and more of the water vapour produced inside the material cannot escape further back into the bulk of the substance anymore but is pushed back towards the hot surface. It redirects this pore pressure which generates explosive spalling when pore pressure exceeds tensile strength of the material [10]. Therefore, spalling is a compromise between mechanical strength and pressure driven by evaporation. Moreover, the differential thermal expansion between the outer and inner regions pushes microchannels to be sealed/closed at the heated face, further exacerbating the risk of spalling by restricting vapor evacuation. A thermal gradient, which may create a so-called "thermal shock" condition, is another cause for explosive spalling. They have incorporated steel, glass, carbon and nylon fibers to it is used to reduce cracking and shrinkage in conventional concretes It has been available for propagation for over 60 years. Polypropylene (PP) fibers commonly used in concretes and refractory castable has changed little since its invention in the early 1970s. Not only contributes to mechanical strength of green castable, Fibers have been reported to be used, instead a strategy that reduces the chances of both structural damage and spalling during drying and first heat-up [11–14].

Refractories are ceramic materials that can withstand high temperatures above 1500 ºC and the refractoriness is determined by its pyrometric cone equivalent. Industries utilize silica fume and fly ash as inexpensive raw materials to prepare refractory composites. Mullite ceramic ($3Al_2O_3{\cdot}2SiO_2$) is an engineering ceramic material that has high strength and high creep resistance at elevated temperatures, low thermal expansion co-efficient and relative thermal stability. Due to its low coefficient of thermal expansion and stable structure, cordierite ceramics ($Mg_2Al_4Si_5O_{18}$) can be used as the carrier of environmental catalysts [15], [16]. So many research studies have been done so far until now on mullite ($3Al_2O_3$-$2SiO_2$) being a multiphase mineral: low thermal expansion and conductivity, great creepy resistance, high temperature strength, along with good chemical stability [17], [18]. Several studies have added oxides such as CaO, MgO, TiO_2, ZrO_2 to improve friction resistance, corrosion resistance, and thermal shock resistance of ceramics [18–23].

1.3. Objective and Scope

This study aims to document the application of ceramic fibers and refractory castable in a single furnace installation. It is important to emphasize that this work is presented as a report study, as the materials were applied in different furnace zones under different. Therefore, this study does not attempt to compare the two materials directly. It also does not provide operational validation or lifecycle cost analysis. The sole purpose of this paper is to document the as-built lining specification, installation procedures, and theoretical thermal modeling of this specific furnace. As a descriptive case report, this study does not propose or test any hypothesis.

2. Methodology

2.1. Case Study Approach

This study adopts a field-based observational approach, focusing on the furnace installed at Haditha Refinery. No experimental measurement protocols were applied because this is an observational case report based on existing installation records, manufacturer data, and laboratory test reports. No field instrumentation (thermocouples, flow meters) was installed at the time of construction. The evaluation is based on:

- Manufacturer specifications
- Laboratory test results
- Field observations during installation

2.2. Crude Oil Heating Furnaces in Refineries

The petroleum industry employs several furnace configurations for crude oil heating applications, as illustrated in Figure (1). These include: [24]

- **Type A:** Coiled box heater.
- **Type B:** Heater Helically cylindrical with heater formed as coil.
- **Type C:** The cabin heater with This construction of the coils of horizontal tube is also rectangular in foot Form.
- **Type D:** Vertically orientated tube-coil heater with the boiler box.
- **Type E:** Tubular, Vertical tube coil arrangement, heater.
- **Type F:** Box heater with vertical Tube Coil Assembly.

The present study is narrowed down in the Type C furnace design, as reported in Figure (1) and Figure (2 a-b) which are used in the Haditha Refinery to heat crude oil to working temperatures of 340 ºC. Later paragraphs will give in-depth information about the furnace parts and thermal lining applications which are the main topic of the current study.

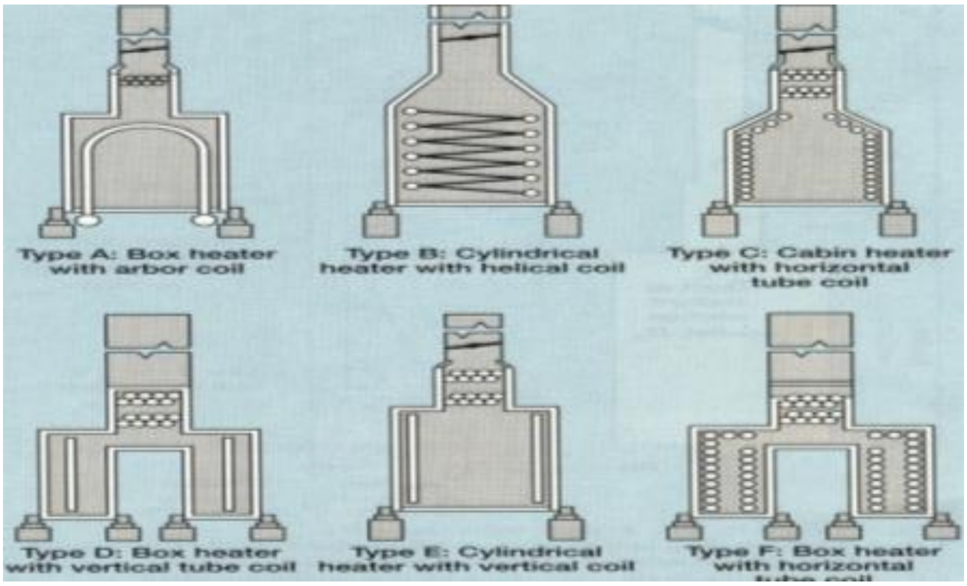

Fig. (1): The main types of furnaces in refineries [1]

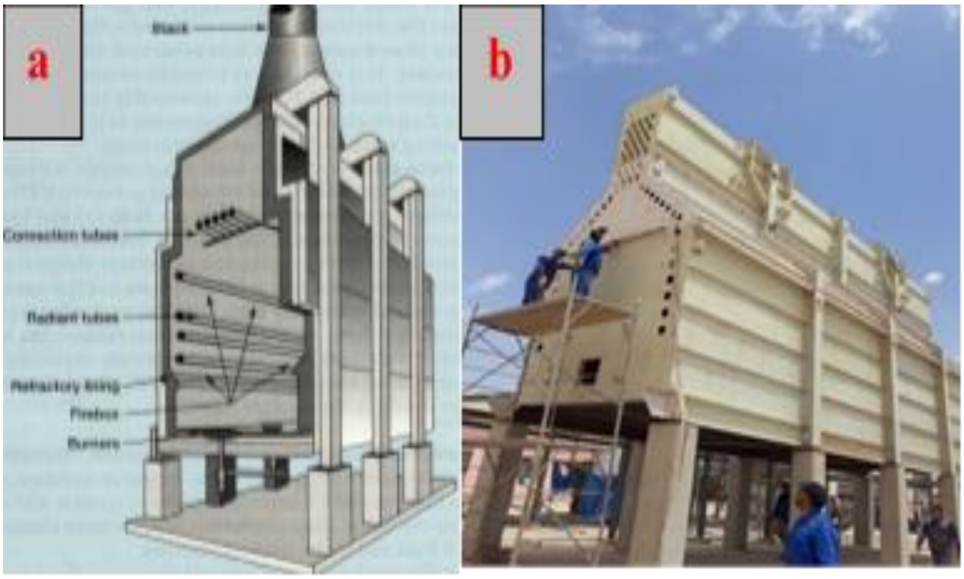

Fig. (2): Type C cabin heater furnace at Haditha Refinery: (a) Primary structural components: (b) Installed assembly and piping. [1]

2.2.1. Furnace Operating Context and Lining Zone Definitions

The crude oil heating furnace at Haditha Refinery processes approximately 10,000 barrels per day, heating crude oil from ambient temperature to 340 ºC before atmospheric distillation. The furnace is designed for dual fuel operation primarily fuel gas (refinery off-gas, mainly methane and light hydrocarbons) with fuel oil as a backup or supplementary fuel depending on availability and refinery economics. When firing fuel oil (typical sulfur content 2.5-3.5%), flue gases contain SO_x, particulate matter, and ash deposits; when firing fuel gas, combustion is cleaner with minimal particulates. This dual fuel context influences the selection of lining materials: ceramic fiber in the radiation zone must resist both thermal shock and occasional chemical attack from fuel oil combustion products, while refractory castable in the convection zones must withstand potential erosion from particulate laden flue gases when fuel oil is used. The furnace is divided into three distinct thermal zones based on heat transfer mechanism and temperature, as illustrated in Figure (2a):

- Section A (Radiation Zone): Contains the burners and firebox. Heat transfer is dominated by thermal radiation from the flame and hot refractory surfaces. The design hot face temperature is approximately 800 ºC. This zone experiences rapid thermal cycling during start-up and shut-down, as well as direct flame impingement. Ceramic fiber was selected for this zone due to its low thermal mass, high thermal shock resistance, and ease of installation around complex geometries.
- Sections B and C (Convection Zones): Located above the radiation zone, these sections contain horizontal tube banks. Heat transfer occurs primarily by forced convection from flue gases passing over the tubes. The design hot face temperature is approximately 450 ºC. These zones experience steady-state operation with lower thermal gradients but higher flue gas velocities (5-10 m/s) that can cause erosion, especially when firing fuel oil that produces fly ash. Refractory castable was selected for these zones and for the front/back headers due to its superior mechanical strength and erosion resistance.
- Stacks: The uppermost sections that exhaust flue gases to atmosphere. These are lined with refractory castable (5 cm thickness) to protect the steel shell from residual heat and acidic condensate (the latter more relevant when firing high-sulfur fuel oil).

The selection of different lining materials for different zones was based on operational requirements (temperature, thermal cycling, erosion potential, fuel flexibility, and installation practicality), not on a research objective to compare material performance. This case report documents the as-built installation; no direct comparison between ceramic fiber and refractory castable is possible because their operating conditions differ fundamentally.

2.3. Theoretical Simulation Performance Evaluation

The heat transfer analysis was conducted to estimate thermal performance. Heat loss through furnace linings was evaluated using steady-state one-dimensional conduction assumptions.

The governing equation is based on Fourier's law: The evaluation criteria for theoretical performance were: (i) steady-state one-dimensional heat conduction (Fourier's law), (ii) thermal conductivity values taken as the mean of manufacturer-reported ranges (0.25 W/m·K for ceramic fiber, 0.80 W/m·K for refractory castable), (iii) hot face temperatures from furnace design specifications (800 ºC for radiation zone, 450 ºC for convection zones), (iv) a fixed cold-face temperature of 60 ºC representing typical external shell conditions, and (v) actual installed lining thicknesses (0.05 m for ceramic fiber blanket; 0.127 m for castable walls; 0.05 m for castable stacks/headers).

$$q = k\,(T_{hot} - T_{cold})/L$$

Where:

q = heat flux (W/m^2).

k = thermal conductivity (W/m.k).

T_{hot} = hot face temperature (convection/radiation zone (ºC).

T_{cold} = 60 ºC (assumed typical external shell condition).

L = lining thickness (m).

Material properties were obtained from manufacturer data and laboratory testing. The analysis provides indicative comparisons rather than exact operational performance.

Two analyses were performed:

1. Actual conditions (different hot temperature (T_{hot}) for each material).

2. Normalized comparison (both at 800 °C, same thickness) for illustration only, not representing real operation.

2.4. Simulation Implementation

Microsoft Excel was used for all calculations. No field temperature or fuel consumption data were collected. All numerical results presented in Sections 4 and 5 are therefore theoretical and should not be interpreted as measured performance.

2.5. Thermal Insulation Systems in Oil Refinery Furnaces

2.5.1. Designing Refractory Lining Systems

An understanding of the primary purpose of the refractory lining is needed to design an effective and reliable ceramic layer system. What is the primary purpose of lining? Is it tied to temperature, erosion, environmental stability, structural stability or chemical stability? It is crucial to understand the process and then how the refractory lining system responds with respect to that process [24].

Elements of refractory design include:

• Lining thickness

• Choice of refractory
• Heat transfer
• Choice of anchoring.

- Lining Thickness

The function or purpose of the refractory lining is related to lining thickness. For the thermal protective lining, the cold-face or shell temperature determines the required thickness. If the primary function of the lining is to resist erosion, then determination of linings thickness is based on the aggressiveness of erosive media and duration required for line service.

Refractory Selection

The success of refractory lining relies primarily on the selection of refractory. While physical properties do not correlate with the performance of a refractory, experience with using these in conjunction with historical data will guide one through the selection process and enhance the chances of designing a quality lining.

- Heat Transfer

The thermal conductivity of the materials defines heat transfer through a refractory lining. The manufacturer usually supplies the thermal conductivity of a refractory but the measuring method is crucial. The refractory thermal conductivity test is based upon the type of refractory and listed in ASTM Volume 15.01.

- Choice of Anchoring

Anchor selection depends upon a number of factors:

• Lining thickness
• Type (coke, oxidate, erosion, water)
• Lining type
• Insulating products
• Dense materials
• Thermal cycling
• Vibration
• External versus internal
• Temperature.

Anchor placement directly affects lining reliability and stability, as well as potential hot-gas bypassing and/or hot-spot development. For all refractory lining systems, a complete review of anchor requirements is also sensible.

2.5.2. Refractory materials functional and classification

Refractories are critical to protecting industrial equipment and aiding in the efficiency and safety of high-temperature industrial processes. Based on their chemical behavior they are broadly classified into three main types, viz: acidic, basic and neutral. Acidic refractories (e.g., silica [SiO_2], fireclay) are resistant to acidic slags but easily attacked by basic materials. Basic refractories, such as magnesite (MgO)and dolomite [$CaMg(CO_3)_2$], exhibit stability in the presence of basic slags and environments, thus making them ideal for steelmaking applications. Neutral refractories (e.g., alumina (Al_2O_3) and chromite ($FeCr_2O_4$) are relatively resistant to both acidic and basics lags, leading to their extensive applications in various industries. Proper differentiation and selection of different types of refractories is pivotal to optimizing thermal performances and durability in a given industrial context [2], [25].

2.6. Limitations of This Case Report

This study has the following limitations:

(1) Ceramic fiber and refractory castable were installed in different furnace zones (radiation vs. convection) with different temperatures and heat transfer modes. No direct material comparison is possible.

(2) No operational data (fuel consumption, external shell temperatures, degradation over time) were collected. All performance estimates are theoretical.

(3) No lifecycle cost analysis was performed. No cost claims are made. Any discussion of potential cost savings in Section 3.2.2 is purely qualitative and does not constitute a verified economic claim.

(4) Material properties are from manufacturer datasheets, not from in-service measurements.

3. Refractory Application

3.1. Refractory Castable Application

3.1.1. Technical Requirements and Performance Characteristics.

The internal surface area of refractory castable system is about 248 m^2. They are convection zones (Section B and C), back and front header and the stacks[1] as well as some of the significant technical parameters are:

- The highest temperature for operating is 1650 ^oC.
- Dry density is 2200-2500 kg/m^3.
- Thermal conductivity: 0.6–1.0 W/m^2 K.
- Cold crushing strength: it is around 60 Mpa;

- Chemical composition: Al_2O_3 (75%), Fe_2O_3 (25%) and SiO_2 and several small additives.
- When burnt, it is able to receive acidic and sulphurous gases that tend to be chemically resistant.
- Flue gas erosion resistance: This is good in flue gas erosion resistance.
- Life expectancy: more than 15 years, special purpose.
- The supplier, in this case, is the MEKSAN Company of Turkey.
- The time frame of delivery: 70 days that would include production of the product, and its delivery.
- Storage facilities: dry and shelf life (6 months).

3.1.2. Installation Methodology and Quality Assurance

The installation process strictly adhered to quality assurance plans outlined in Figure 4(a-d) [1]. Surface preparation and cleaning of Sections B and C to rid the surfaces of any contaminants and welding slag.

- Anchoring systems via 6 mm diameter welding wire pins were V-patterned and spaced at 20 cm. The wall anchor height was 10 cm, whereas the stack and header anchor height was 4 cm, as depicted in Figure (3j) and Figure (4, a-b) [1], [26], [27].
- Formwork construction through 20mm thick plywood, casted in 1m lifts with proper wooden and metal supports shown in Figure (4, c-d) to preclude any formwork movement.
- Mixing procedures were contingent on the use of reverse osmosis water at 20-25 °C; moreover, the water-to-powder ratios were not to exceed 15%. Total mix time was not to exceed 10 min to avoid premature mix setting [26], [28–30].
- Placement operations were coupled with continuous mechanical vibration to avoid any air voids, and these reduced the wall thickness approximated at 12.7 cm and 5 cm for stacks and headers.
- Curing and drying operations included retaining the formwork for 48-72 h, then dowsing the blocks continually with water via a remover followed by drying at a controlled burner with a 300 °C distance and a 50 °C/h rate.

Upon the arrival of all quantities at the Haditha site, the resident engineer, alongside the work supervisor of Haditha Refinery, took by random samples that were sent via the Haditha Refinery manager in an official letter to the Building Research Center of the Ministry of Housing and Construction.[31] The cement, granite, silica, and the polypropylene straps passed all mechanical and chemical analyses in the laboratory. The results were compared with the manufacturers' data sheet.

All results were in tandem with the suggested specifications as clearly enumerated in Table (1 a-b). Additionally, Table (2) describes the technical specifications data sheet of the supplier namely: MEKSAN Turkish Company [28].

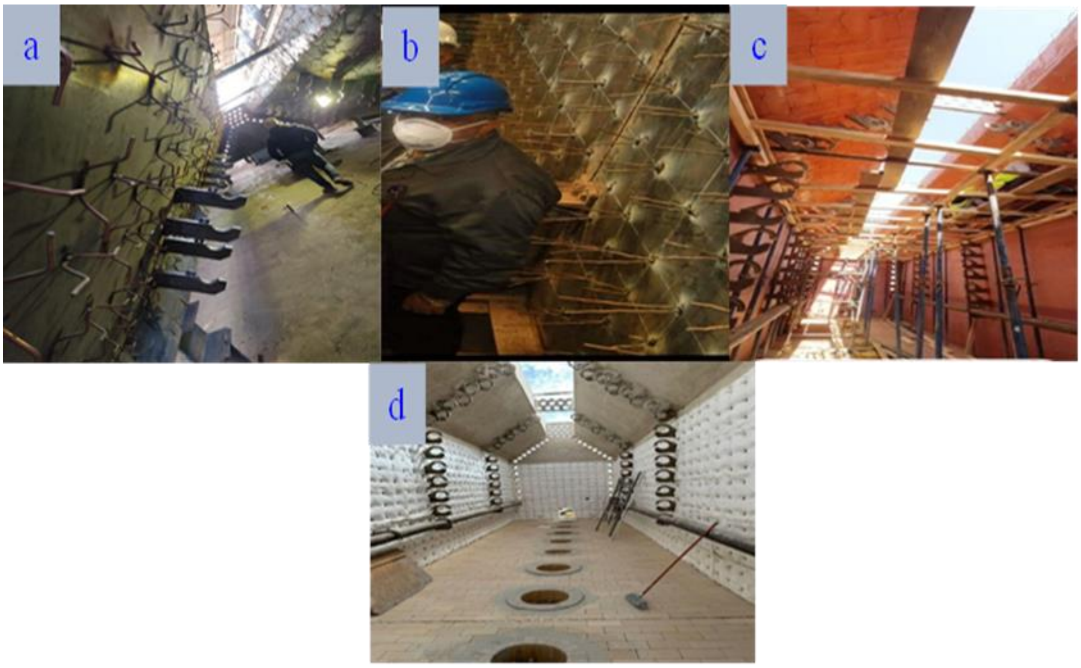

Fig. (4): Refractory lining installation sequence for furnace sections: **(a)** Section C wall with completed metal anchor reinforcement grid: **(b)** Close-up of the welded anchor pattern on the Section C wall: **(c)** Installation of wooden formwork inside Section B prior to casting: **(d)** Section B after formwork removal, showing the finished refractory lining.[1]

Table (1): Laboratory test results; **(a)** examination and **(b)** chemical examination for the physical refractory castable from the Building Research Center. [31]

a) Physical Examination	
Examination Type	**Result%**
Thermal loading at 1200 °C	No melting or deformation occurred on the sample
b) Chemical Examination	
Oxides	**Result%**
L.O.I	0.49
SiO_3	43.59
AL_2O_3	51.04
Fe_2O_3	1.22
SO_3	NilL
CaO	2.99
MgO	0.66
Total	99.99

Table (2): Laboratory test results; **(a)** physical examination and **(b)** chemical examination for the refractory castable used in the thermal lining of furnace walls from MEKSAN Company. [28]

Physical Properties	
Temperature Value	110 °C
Cold Crushing strength (kg/cm^3)	400
Bulk Density (g/cm^3)	2.25
Chemical Analysis (%)	**Result%**
Al_2O_3	63.2
SiO_3	28
Fe_2O_3	1.5
TiO_3	2
CaO	5.0
MgO	-
Alkali	0.5

3.2. Refractory Ceramic Fiber Application

3.2.1. Considerations when Choosing Ceramic Fiber for Different Types of Furnaces

Choosing the correct type of ceramic fiber is essential to ensure optimal performance and long furnace life in various industrial applications. Considering the following factors, the most suitable ceramic fiber can be selected for specific needs:[1]

- The operating temperature of the furnace: Different types of ceramic fiber are designed to withstand various temperature ranges. Standard grades may be suitable for temperatures up to 2300 °F (1260 °C), while high-temperature grades can withstand conditions up to 3000 °F (1650 °C).
- Chemical resistance and compatibility with processed materials: The chemical resistance of ceramic fiber and its compatibility with the materials processed in the furnace are critical considerations, especially in applications where corrosive or aggressive chemicals are handled.
- Furnace Liner Size and Shape Requirements: Some furnaces may have complex geometries or require customized linings to suit their specific applications. It is crucial to select the appropriate ceramic fiber product that can quickly adapt to diverse shapes and sizes without compromising its structural integrity or thermal performance.

The right choice of ceramic fiber improves process efficiency and contributes to the safety and quality of the final product, ensuring the long-term success of industrial operations.

3.2.2. Installation Process and Maintenance Costs

No cost-benefit or lifecycle cost analysis was performed for this installation. The following discussion describes general considerations for ceramic fiber linings but does not provide specific cost data or claims for the Haditha furnace. While the selection of the right lining for an industrial furnace is a performance and durability/cost analysis task for any such equipment, the evaluation of costs must be based on the installed cost for the first time and its maintenance cost over the life cycle of the equipment. In regard to ceramic fiber, this can also depend on a number of variables:

- Installations needed upfront: Installation costs depend on material, labor, equipment, and tooling.
- Long-term maintenance: While designed for durability and thermal shock resistance, ceramic fiber still needs periodic maintenance to ensure optimal service over time.

This would require maintenance that could range from the periodic inspection of the lining for signs of damage or wear, minor repairs in order to correct cracks or areas that have degraded, to complete replacement of the lining if it experienced damage that could not be repaired or if the lining was worn too severely. It's essential to do an evaluation of a ceramic fiber-lined furnace, weighing the capital outlay against ongoing and maintenance costs- plus the gains from enhanced performance, energy savings, and longer life of equipment. Although ceramic fiber may have higher upfront material costs, its lower thermal conductivity can reduce theoretical heat loss. However, no lifecycle cost analysis or operational fuel savings data are available from this installation.[1]

3.2.3. Ceramic Fibers Application

Thermal lining in the radiation zone (Section A) of the furnace was done with ceramic fibers and the area of internal wall surface covered was approximately 103 m^2 as per the following technical specifications:[1], [18]

- Resists temperatures up to 1250 ºC and does not expand or contract in heat.
- Low Thermal Conductivity: 0.2-0.27 W/m^2 K, and therefore, it is an excellent thermal insulator.
- Thermal Shock Resistance: Lightweight and low-density characteristics do not cause cracks in the ceramic lining by allowing sudden changes in temperature (surge or rapid decrease).
- Chemical Resistance: The ceramic fiber resists sulfuric and alkaline acids and vapors particularly relevant when firing fuel oil (which contains sulfur) as part of the furnace's dual-fuel operation. When firing fuel gas, chemical attack is minimal.

- Low Heat Storage: The density and lightness of the ceramic fiber material is able to absorb and lose heat rapidly thus giving the furnace a high rate of heating and cooling. Heat contained in the ceramic fiber is 2700-4050 kcal/m^2 as compared to 54200-49390 kcal/m^2 of refractory castable.
- Low Density: The density of the ceramic fibers employed in lining of Section A of the furnaces of Haditha Refinery is 128 kg/m^2 in contrast to the density of the refractory castable employed in the lining of other parts of the furnaces (B, C) which is 2250 kg/m^2, which implies that the ceramic fibers are 20 times lighter than the refractory castable.
- Chemical Composition:

  I. The type of Alumina-Silica as per the following ratios:
- Alumina (Al_2O_3) at 42-47%
- Silica (SiO_2) at 48-54%

  II. Small traces of (CaO, MgO, TiO_2, KO, NaO).
- Lifespan: Ceramic fibers have a lifespan of 10-15 years based on the operating conditions and the fuel type to be used in the furnace to heat it. Light fuel such as natural gas consumption decreases the deposits of combustion and melts, thus stretching ceramic fibers life. Because the Haditha furnace is designed for dual-fuel operation (fuel gas and fuel oil), the actual lifespan may vary. Cleaner fuels such as natural gas (or fuel gas) reduce combustion deposits and slagging, extending ceramic fiber life. When firing fuel oil, more frequent inspection is recommended due to potential ash adhesion and chemical attack.
- Energy Conservation (theoretical estimate): Based on manufacturer specifications, ceramic fiber is claimed to provide better thermal insulation than refractory castable. A theoretical calculation (see Section 4) suggests potential fuel savings under identical conditions, but this is not a measured value from the Haditha furnace.
- Manufacturing Flexibility: The manufacture of ceramic fibers is done in various shapes and sizes according to the necessity and where to be used like blankets, boards. The density of the blankets used to line Haditha furnace be 128 kg /m^3 with dimensions (5 cm thickness /61 cm width /360 cm length) per piece.
- Manufacturing and Preparation Period to Work Site: One month after the date of opening the work order in the manufacturing company.
- Manufacturer: RAVATHERM Company (Turkey), the specifications data sheet of the ceramic product as:[32]

- Length = 610*3600 (mm*mm).
- Thickness = 50 mm.
- Density = 128 Kg/m^3
- Pack = 2.196 m^2

- Checking Party in Iraq (Third Party): The samples of ceramic fibers were submitted to the laboratories of Al-Rakhl Engineering Inspection Company which is a third party that is accredited in the Iraqi Ministry of Oil and the necessary thermal endurance tests were performed in the company and the results were found to be of the necessary specifications.

4. Results

The following heat flux values are theoretical estimates derived from manufacturer specifications and Fourier's law. They do not represent measured in-service performance.

4.1. Heat Loss Estimation

A simplified steady-state heat transfer calculation was conducted using the actual installed lining thicknesses and Fourier's law:

$$q = k\ (T_{hot} - T_{cold})/L$$

Where:

q = heat flux (W/m^2)

k = thermal conductivity (W/m K)

T_{hot} = hot face temperature (ºC)

T_{cold} = cold face temperature (60 ºC assumed typical external shell condition)

L = Lining thickness (m)

The following actual installed thicknesses were used, as documented in Sections 3.1.2 and 3.2.3: ceramic fiber blanket in the radiation zone (Section A) – 0.05 m (5 cm); refractory castable on the walls of convection zones (Sections B and C) – 0.127 m (12.7 cm); and refractory castable on stacks and headers – 0.05 m (5 cm). Thermal conductivity values were taken from manufacturer datasheets: 0.25 W/m K for ceramic fiber (mean of 0.2–0.27) and 0.80 W/m K for refractory castable (mean of 0.6–1.0). Estimated heat flux:

Ceramic fiber (Section A, radiation zone, T_{hot} = 800 ºC, k = 0.25 W/m·K, L = 0.05 m):

q = 0.25 × (800 − 60) / 0.05 = 3700 W/m^2

Total heat loss (103 m^2) = 3700 x103 = 381 kW

Refractory castable- stacks and headers (T_{hot} = 450 ºC, k = 0.8 W/m·K, L = 0.127 m):

$q = 0.8 \times (450 - 60) / 0.127 = 2457$ W/m^2

Total heat loss (200 m^2) = 2454 x 200 = 491 kW

Refractory castable- convection zone (T_{hot} = 450 ºC, k = 0.8 W/m·K, L = 0.05 m):

$q = 0.8 \times (450 - 60) / 0.05 = 6240$ W/m^2

Total heat loss (50 m^2) = 6240 x 50 = 312 kW

Total for all refractory castable areas (250 m^2): 491 + 312 = 803 kW

Area-weighted average heat flux = 803 / 250 = 3210 W/m^2.

These values are presented for each material under its own operating conditions. No direct comparison is possible due to different temperatures, heat transfer modes, and thicknesses.

4.2. Normalized Comparison (Same Temperature, 800 ºC)

To illustrate thermal resistance differences only (not representing actual furnace operation):

- Ceramic fiber: 1850 W/m^2
- Refractory castable: $0.80 \times (800 - 60) / 0.10 = 5920$ W/m^2

This normalized comparison is for illustration of thermal resistance differences only. It does not represent actual furnace operation because the materials were never installed under identical conditions.

4.3. Theoretical Fuel Savings Estimate

A purely illustrative calculation based on normalized heat flux differences suggests a potential reduction in heat loss under identical hypothetical conditions. No percentage savings are reported because the calculation is not validated by operational data. The authors emphasize that this is not a measured fuel saving and should not be cited as such.

5. Discussion

This case report documents a real-world installation of ceramic fiber and refractory castable in a single refinery furnace. Comparing the theoretical heat flux values obtained in this study with published literature[4,33] shows that ceramic fiber typically exhibits 40–60% lower heat loss than dense castable when tested under identical laboratory conditions or in identical furnace zones. However, those studies used controlled setups where all variables except the lining material were kept constant. The present case report cannot confirm such differences because the materials were installed in different zones of the Haditha furnace radiation zone at 800 ºC versus convection zones at 450 ºC with different heat transfer mechanisms (radiation vs. convection) and different mechanical stresses. The lack of operational data (external shell temperatures, fuel consumption records, material degradation over time) is a major limitation of this case report. Future work should instrument the furnace with thermocouples on the external shell and flow meters on the fuel line to collect real-time heat flux and fuel usage over at least one full operating cycle (e.g., 12 months). Such data would allow validation or refinement of the theoretical models presented here and would provide a basis for actual performance comparison under real operating conditions. However, the following critical limitations prevent any direct material comparison or generalizable conclusion:

1. Different operating conditions: The radiation zone (800 ºC, primarily radiation heat transfer) and convection zones (450 ºC, convection-dominated) are fundamentally different. Any performance difference cannot be uniquely attributed to the material. Readers should not interpret the theoretical heat flux values as evidence of ceramic fiber superiority, because the two materials operated under fundamentally different temperatures, thicknesses, and heat transfer mechanisms.
2. No operational validation: No external shell temperatures, fuel consumption records, or long-term degradation data were collected. All “fuel savings” claims remain theoretical. Retrofitting the Haditha furnace with thermocouples and flow meters would require a scheduled shutdown, which is not anticipated within the next 18 months. Consequently, no operational validation is currently possible.
3. No lifecycle cost analysis: Material costs, installation labor, maintenance, and lifespan were not analyzed. Economic superiority is not established.
4. Manufacturer-dependent data-Material properties were supplied by MEKSAN and RAVATHERM; third-party testing (Building Research Center, Al-Rakhl) confirmed specifications but did not measure in-service performance.

6. Conclusions

- Ceramic fiber and refractory castable were successfully installed in different zones of a Haditha Refinery furnace (2023).
- Theoretical steady-state simulations gave estimated heat fluxes of 1850 W/m^2 for ceramic fiber (radiation zone, 800 ºC) and 3120 W/m^2 for refractory castable (convection zone, 450 ºC).
- Because the materials were installed in zones with different temperatures, heat transfer modes, and mechanical stresses, no direct comparison of material performance is possible.
- All heat loss and fuel saving estimates are theoretical; no operational measurements were collected.

- Future work should include field measurements (shell temperatures, fuel consumption) over a full operational cycle to validate theoretical models.

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