Analysis of Industrial Process Heater using Thermography

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Abstract - *Infrared thermography, thermal imaging, and thermal video are examples of thermal imaging science. Thermal imaging cameras usually detect radiation in the long-infrared range of the electromagnetic spectrum (roughly 9000-4000 nanometers or 9–14 µm) and produce images of that radiation, called thermograms. Since infrared radiation is emitted by all objects with a temperature above absolute zero according to the black body radiation law, thermography makes it possible to see one's environment with or without visible illumination. The amount of radiation emitted by an object increases with temperature; therefore, thermography allows one to see variations in temperature. When viewed through a thermal imaging camera, warm objects stand out well against cooler backgrounds; humans and other warm-blooded animals become easily visible against the environment, day or night. As a result, thermography is particularly useful to the military and other users of surveillance cameras.*

Process heaters are a critical component in the refining of crude oil. Similar in construction to a steam boiler, process heaters are used to heat crude oil by passing it through steel tubes located within the firebox of the furnace. Critical to the safe and efficient operation of the furnace is the operating temperature of tubes within the furnace. By using a thermal imager designed specifically for infrared inspections of operating heater tubes, it is possible to perform quantitative infrared inspections and monitor temperature of tubes within an operating furnace. This paper will discuss the application of thermography for process heater tubes and share insights from a project where thermographic monitoring was employed on a daily basis to help ensure safe operation of an operating crude furnace.

***Key Words*: Infrared thermography, thermal imaging, Industrial process heater, Thermal imaging camera, Refinery, Infrared inspections**

1. INTRODUCTION

Thermography is a method of inspecting electrical and mechanical equipment by obtaining heat distribution pictures. This inspection method is based on the fact that most components in a system show an increase in temperature when malfunctioning. The increase in temperature in an electrical circuit could be due to loose connections or a worn bearing in the case of mechanical equipment. By observing the heat patterns in operational system components, faults can be located and their seriousness evaluated.

The inspection tool used for thermography is the Thermal Imager. These are sophisticated devices which measure the natural emissions of infrared radiation from a heated object and produce a thermal picture. Modern Thermal Imagers are portable with easily operated controls. As physical contact with the system is not required, inspections can be made under full operational conditions resulting in no loss of production or downtime.

An oil refinery is a large, complex, and very specialized industrial site. Its purpose is to transform crude oil from its unprocessed state into various chemical products and by-products. Common end materials from the refinery process include gasoline, heating oils, ingredients for plastics, and many other common products. A typical refinery consists of a vast number of heaters, boilers, pipelines, processing towers, and machineries. Since these heaters , boilers etc works at very high temperatures, it will be very difficult to conduct inspections with our naked eye. Here, In this paper a detailed analysis of one of the sophisticated method of inspection of industrial process heater is discussed.

1.1 Infrared Theory

An object when heated radiates electromagnetic energy. The amount of energy is related to the object's temperature. The energy from a heated object is radiated at different levels across the electromagnetic spectrum. In most industrial applications it is the energy radiated at infrared wavelengths which is used to determine the object's temperature. Figure shows various forms of radiated energy in the electromagnetic spectrum including X-rays, Ultra Violet, Infrared and Radio. They are all emitted in the form of a wave and travel at the speed of light. The only difference between them is their wavelength which is related to frequency. The human eye responds to visible light in the range 0.4 to 0.75 microns.

Infrared Radiation (IR) is electromagnetic radiation with longer wavelengths than those of visible light, and is therefore invisible to the human eye. Infrared radiation is emitted or absorbed by molecules when they change their rotational-vibrational movements. It excites vibrational modes in a molecule through a change in the dipole moment, making it a useful frequency range for study of these energy states for molecules of the proper symmetry.

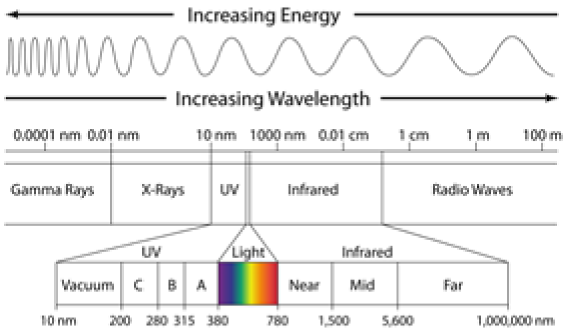

Fig-1: Electromagnetic spectrum

Infrared radiation is used in industrial, scientific, and medical applications. Night-vision devices using active near-infrared illumination allow people or animals to be observed without the observer being detected. Infrared astronomy uses sensor-equipped telescopes to penetrate dusty regions of space such as molecular clouds, detect objects such as planets, and to view highly red-shifted objects from the early days of the universe. Infrared thermal-imaging cameras are used to detect heat loss in insulated systems, to observe changing blood flow in the skin, and to detect overheating of electrical apparatus.

2. THERMOGRAPHIC CAMERA

A thermal imaging camera records the intensity of radiation in the infrared part of the electromagnetic spectrum and converts it to a visible image. Our eyes are detectors that are designed to detect electromagnetic radiation in the visible light spectrum. All other forms of electromagnetic radiation, such as infrared, are invisible to the human eye.

Although infrared radiation (IR) is not detectable by the human eye, an IR camera can convert it to a visual image that depicts thermal variations across an object or scene. IR covers a portion of the electromagnetic spectrum from approximately 900 to 14,000 manometers (0.9–14 µm). IR is emitted by all objects at temperatures above absolute zero, and the amount of radiation increases with temperature. Thermography is a type of imaging that is accomplished with an IR camera calibrated to display temperature values across an object or scene. Therefore, thermography allows one to make non-contact measurements of an object's temperature.

2.1 Working

Infrared energy (A) coming from an object is focused by the optics (B) onto an infrared detector (C). The detector sends the information to sensor electronics (D) for image processing. The electronics translate the data coming from the detector into an image (E) that can be viewed in the viewfinder or on a standard video monitor or LCD screen.

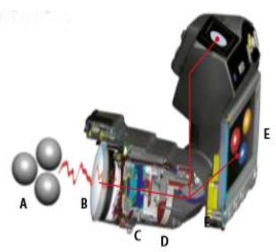

Fig 2: Thermographic Camera

Infrared thermography is the art of transforming an infrared image into a radiometric one, which allows temperature values to be read from the image. So every pixel in the radiometric image is in fact a temperature measurement. In order to do this, complex algorithms are incorporated into the thermal imaging camera. This makes the thermal imaging camera a perfect tool for Science R&D applications.

Fig 4: FLIR GF 309 Thermal Imaging Camera

2.2 Camera Constructions

IR camera construction is similar to a digital video camera. The main components are a lens that focuses IR onto a detector, plus electronics and software for processing and displaying the signals and images. Instead of a charge coupled device that video and digital still cameras use, the IR camera detector is a focal plane array (FPA) of micrometer size pixels made of various materials sensitive to IR wavelengths. FPA resolution can range from about 160 × 120 pixels up to 1024 × 1024 pixels. Certain IR cameras have built-in software that allows the user to focus on specific areas of the FPA and calculate the temperature. Other systems utilized a computer or data system with specialized software that provides temperature analysis. Both methods can supply temperature analysis with better than ±1°C precision.

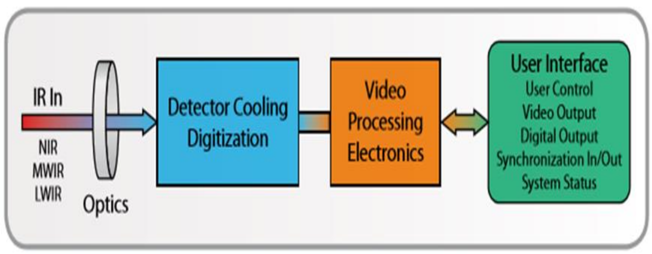

Fig 3: Simple Block Diagram of a Thermographic Camera

FPA detector technologies are broken down into two categories: thermal detectors and quantum detectors. A common type of thermal detector is an uncooled microbolometer made of a metal or semiconductor material. These typically have lower cost and a broader IR spectral response than quantum detectors. Still, microbolometers react to incident radiant energy and are much slower and less sensitive than quantum detectors. Quantum detectors are made from materials such as InSb, InGaAs, PtSi, HgCdTe (MCT), and layered GaAs/AlGaAs for QWIP (Quantum Well Infrared Photon) detectors. The operation of a quantum detector is based on the change of state of electrons in a crystal structure reacting to incident photons. These detectors are generally faster and more sensitive than thermal detectors. However, they require cooling, sometimes down to cryogenic temperatures using liquid nitrogen or a small stirling cycle refrigerator unit.

3. INDUSTRIAL PROCESS HEATER

Heaters play an important role in both the petroleum and petrochemical refinery. They provide the necessary heat to hydrocarbons of all types from crude oil and asphalt to lighter hydrocarbon fluids or gases. A direct fired heater or an industrial furnace, is an equipment used to provide heat for a process or can serve as a reactor which provides heats of reaction. Fired heaters have a coil or coils of tubing through which the process fluids or gases flow and are enclosed in a setting that is fired. Furnace designs vary as to its function, heating duty, type of fuel and method of introducing combustion air. However, most process furnaces have some common features.

Firing is accomplished by the burning of either a liquid or gaseous fuel. Fuel flows into the burner and is burnt with air provided from an air blower. There can be more than one burner in a particular furnace which can be arranged in cells which heat a particular set of tubes. Burners can also be floor mounted, wall mounted or roof mounted depending on design. The flames heat up the tubes, which in turn heat the fluid inside the tubes. The heat produced by the combustion of fuel is transferred to the process fluid inside the tubes by three different modes of heat transfer.

3.1 Working

Fuel flows into the burner and is burnt with air provided from an air blower. There can be more than one burner in a particular furnace which can be arranged in cells which heat a particular set of tubes. Burners can also be floor mounted, wall mounted or roof mounted depending on design. The flames heat up the tubes, which in turn heat the fluid inside in the first part of the furnace known as the radiant section or firebox. In this chamber where combustion takes place, the heat is transferred mainly by radiation to tubes around the fire in the chamber.

The heating fluid passes through the tubes and is thus heated to the desired temperature. The gases from the combustion are known as flue gas. After the flue gas leaves the firebox, most furnace designs include a convection section where more heat is recovered before venting to the atmosphere through the flue gas stack. Some industries commonly use their furnaces to heat a secondary fluid known as Heat Transfer Fluids (HTF), with special additives like anti-rust and high heat transfer efficiency. This heated fluid is then circulated round the whole plant to heat exchangers to be used wherever heat is needed instead of directly heating the product line as the product or material may be volatile or prone to cracking at the furnace temperature.

4. ANALYSIS

Thermal analysis of Crude Heater (CH-22) is done using a thermal imaging camera (FLIR GF 309). The analysis is conducted on series basis to detect problems or failures that may occur in an industrial process heater. This regular inspection is imperative to ensure proper working of the furnace. Through this inspection, the effects of scale and coke formation, flame impingement on furnace tubes can be identified so that any failure or rupture that may occur to the tubes can be prevented..

4.1 Detailed Procedures

An object can emit thermal radiations when and this emission is related to two things, i.e its temperature and emissivity. In real case, when radiation from the surroundings hit a furnace tubes, most of that energy will be absorbed and some radiation will be reflected.

The camera does not see the temperature and the image is a radiation image rather than a temperature image, it is necessary to compensate the radiations the camera receives, in order to measure temperature. Therefore certain compensation factors should be given as an input to the camera to do all the calculations.

The furnace tube will have an apparent temperature (the radiation the camera will see) that consists of three components; radiation from the atmosphere inside the furnace, and what is left of the emitted and reflected radiations after some has been absorbed by the atmosphere, the transmitted radiation.

What the camera needs to know is the emitted part only, but it receives a total sum of three components. Providing the compensation factors enables the camera to calculate the emitted radiation from the atmosphere and remove it. Then it will replace the loss, the absorbed radiation and the reflected radiation will be removed from the sum of the emitted and reflected radiations.

The compensation factors are;

- Emissivity and reflectivity, ε + ρ = 1, calculated by the camera
- $T_{reflected}$ (Temperature radiated from furnace surroundings)
- Distance between the camera and furnace tube
- Relative humidity
- Atmospheric temperature

Distance will tell the camera how much the atmosphere is emitting and absorbing, or the thickness of the absorbing and emitting layer of gases. Relative humidity and atmospheric temperature together are used to determine how "dense" the atmosphere is, to determine the absorptivity and emissivity of the atmosphere. Atmospheric temperature is used again to calculate the emission from the atmosphere. The only requirement is to input the correct values and the camera will give the correct output.

Having dealt with the atmosphere, the camera now knows what radiation comes from the tubes, the sum of the emitted and reflected radiation. The reflected part needs to be removed from the total radiation from the hot tube, to give the emitted part only.

$T_{reflected}$ is radiation component measured in 0C. The camera sees the radiation, converts it to electrical signals and displace it as 0C. The camera will multiply the radiation corresponds to Treflected and multiply with the reflectivity (1-emissivity) and remove the result from the total of emitted and reflected radiation and gives the emitted radiation only.

- Selecting the value of emissivity

A reasonable assumption for emissivity will be good enough with the following reasoning. It will probably not be over 0.95. It is highly unusual that any surface comes closer to black body emissivity than to 0.95. Carbon and metal oxides have maximum emissivity.It will probably not be less than 0.85. The standard default value of emissivity for furnace tubes is 0.90.

- Temperature calculation

The camera is calibrated to something called a blackbody reference source. So in essence, it only understand blackbodies. A reference source will not be quite a blackbody, but close enough. But the furnace tube is a real body and the radiation emitted from it is less that of a black body. First the radiation signal from the emitted radiation is compensated up to the corresponding signal that a black body would have at that temperature, then the temperature is calculated using the camera`s calibration curve.

- Distance

Distance is the most significant of the three atmospheric compensation factors, and also the easiest one to deal with. In most cases it will be possible to estimate distance from drawings, if not a reasonably good guess will usually be sufficient.

- Relative humidity

It may not be so easy to find out relative humidity, it plays such a small role in the error that may occur and it is suitable to assume a reasonable value.

- Atmospheric Temperature

The value of atmospheric temperature is taken from process data and specifications for the furnace. If the furnace has a convection section, flue gas temperature plus perhaps an estimated addition can be used for the convection section. A thermocouple is employed for the purpose.

After setting suitable values for the camera parameters and compensation factors, thermography of the hot furnace tube of CH-22 heater is done. The procedure involves the following steps;

- Open the peephole by pulling the rope attached to it.
- For taking the thermal image of left side tube, consider the right side tube as a black body by setting emissivity value to 1, the camera will give the value for reflected temperature (Treflected).
- Now by providing the obtained value for reflected temperature, the thermal image of the left side tube is captured.
- The image will give the spot temperature, maximum, minimum and average temperature of the furnace tube. Any defects will be shown as hotter (more bright) than the rest of the parts of the tube.
- The same procedure is adopted for taking the thermal image of the right side furnace tubes.

The design temperature of the CH-22 furnace tube heater is 585^{o}C. When the temperature increases and becomes greater than the design temperature of the tube, high degree of damage mechanisms may takes place. These damages are caused by the excessive heating of a particular part of the tube due to different reasons. The reasons of excessive heating of the tube cannot be identified by our naked eye but only through thermal images of the tubes. For this, suitable analysis of the thermal images are carried out.

5. RESULT

The furnace tube will receive heat flux by convection and radiation. Radiation is the strongest heat transfer mode. Heat flux will reach the first solid surface of the tube, which is usually oxide or scale. Coke and scale will add resistance to the heat flow. The analysis of the images obtained while performing thermography will help to identify the different damages that may occur to the tubes. The result of analysis of the images are as follows;

5.1 Scale Formation

Scale is a solid layer forming on the outside tube surface. It comes from either corrosion products from the steel or solid deposits from the combustion or both. It is inevitable that metal will oxidize at such high temperatures, so there will always a certain degree of scaling taking place. But scaling also depends a lot on fuel quality. Gas will usually give less scale than oil, but gas with high sulphur content will also form a lot of scale, that insulates the outer surface of the tubes. The scale is fairly a compact material, not very porous. It has a strongly varying, but rather high thermal conductivity.

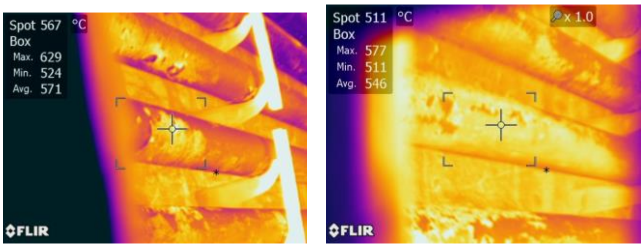

FIG 4: Furnace tube with scales

Scale in an infrared image will have a sharp edged pattern as pieces of scale fall off locally. Thinner scale will form in the bare areas, but the thickness will show as long as scale thickness differ. With a thin layer of scale, before it starts to peel of, the only indication will be a surface temperature increase. The cooler areas are where the scale is thinner and the heat passes through the tube more easily.

5.2 Coke Formation

Coke is solid or semi-solid layer inside the tube that is created when the process fluid is overheated for some reason. The coke has low thermal conductivity, so it has poor conductive heat transfer to the fluid inside the tube. The coke reduces the flow rate of the fluid itself, which reduces output and further coking is more likely to occur. It is a more serious condition than scale formation.

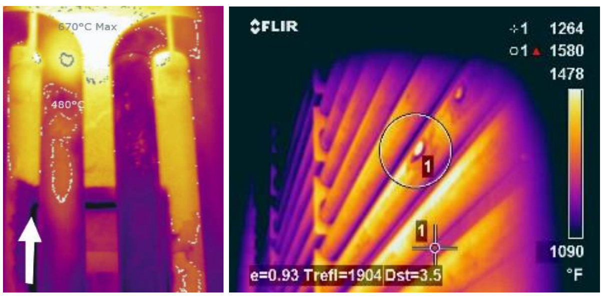

FIG 5: Thermal image of coke formation on Furnace tubes

Coke will show up as a smooth thermal pattern in the infrared image. The areas with coke are hotter than the rest of the tube and heat transfer is more difficult to take place, which results in surface heating of the tubes.

5.3 Flame Impingement

Flame impingement is a condition where the flame strikes the tube directly instead of just radiating towards it. The heating of the tube gets too strong when this happens. The temperature is very high where the flame strikes. This is caused by the flame having irregular pattern, usually due to the problems with the burners.

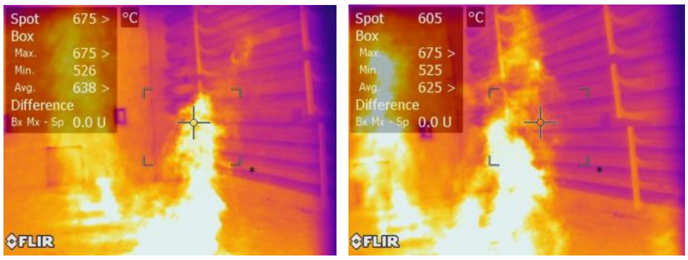

Fig 6: Flame Impingement on furnace tubes

Flame impingement on furnace walls will leads to higher thermal stress, overheat the tube metal locally, which could cause metallurgical changes, micro cracks, increased corrosion etc. Flame impingement can cause hot spot inside the tube that may lead to coke formation and can accelerates the rate of coke formation inside the tube, and if that happens, and the flame impingement persists, the result is even more serious. Patterns from flame impingement varies with flame movement, coke will show more stationary and constant patterns.

5.4 Damage Mechanisms

The different damage mechanisms that may happen to the tube due to these phenomena are;

1. CREEP AND STRESS RUPTURE

At high temperatures, metal components can slowly and continuously deform under load below the yield stress. This time dependent deformation of stressed components is known as creep. Deformation leads to damage that may eventually lead to a rupture. All metals and alloys are affected.

2. THERMAL FATIGUE

Thermal fatigue is the result of cyclic stresses caused by variations in temperature. Damage is in the form of cracking that may occur anywhere in a metallic component where relative movement or differential expansion is constrained, particularly under repeated thermal cycling.

3. THERMAL SHOCK

A form of thermal fatigue cracking – thermal shock – can occur when high and non-uniform thermal stresses develop over a relatively short time in a piece of equipment due to differential expansion or contraction. If the thermal expansion/contraction is restrained, stresses above the yield strength of the material can result. Thermal shock usually occurs when a colder liquid contacts a warmer metal surface.

4. OXIDATION

Oxygen reacts with carbon steel and other alloys at high temperature converting the metal to oxide scale. It is most often present as oxygen in the surrounding air (approximately 20%) used for combustion in fired heaters and boilers. All iron based materials including carbon steel and low alloy steels, both cast and wrought.

5. SULFIDATION

Corrosion of carbon steel and other alloys resulting from their reaction with sulphur compounds in high temperature environments. The presence of hydrogen accelerates corrosion. All iron based materials including carbon steel and low alloy steels, 300 Series SS and 400 Series SS and Nickel base alloys are also affected to varying degrees depending on composition, especially chromium content.

6. CARBURIZATION

Carbon is absorbed into a material at elevated temperature while in contact with a carbonaceous material or carburizing environment.

7. DECARBURIZATION

A condition where steel loses strength due the removal of carbon and carbides leaving only an iron matrix. Decarburization occurs during exposure to high temperatures, during heat treatment, from exposure to fires, or from high temperature service in a gas environment. Carbon steels and low alloy steels are affected.

8. METAL DUSTING

Metal dusting is form of carburization resulting in accelerated localized pitting which occurs in carburizing gases and/or process streams containing carbon and hydrogen. Pits usually form on the surface and may contain soot or graphite dust.

9. FUEL ASH CORROSION

Fuel ash corrosion is accelerated high temperature wastage of materials that occurs when contaminants in the fuel form deposits and melt on the metal surfaces of fired heaters, boilers and gas turbines. Corrosion typically occurs with fuel oil or coal that is contaminated with a combination of sulphur, sodium, potassium and/or vanadium. The resulting molten salts (slags) dissolve the surface oxide and enhance the transport of oxygen to the surface to re-form the iron oxide at the expense of the tube wall or component.

5.5 RECTIFICATION

The problems associated with furnace tubes can be rectified using the following methods.

1. ON-LINE CLEANING FOR SCALE REMOVALS

Chemical cleaning technology is an effective way to improve heater efficiency without shutting down plant operations. This technology is designed to quickly remove deposits such as slag and other fouling materials that build up over time on tube fire side surfaces.

On-line cleaning uses a high-performance, proprietary liquid chemical that has been consistently proven to protect heaters and boilers from damage. During the fired heater cleaning process, the chemical is sprayed through specially designed nozzles, indirectly onto the radiant and convection tubes of the fired heater. The chemical vaporizes and covers the targeted exposed tube surfaces. This process can also clean air preheaters (APH) through specially designed nozzles that inject additional proprietary chemicals into the flue gas. The chemicals vaporize and cover the surfaces of the air preheater, cleaning them in a similar manner as the firebox chemicals. This process can also be done without an APH bypass.

2. OFF-LINE CLEANING FOR SCALE REMOVALS

Off-line cleaning uses mechanical means such as high pressure water jet, sand blasting or manual labor using steel brushes. During Off-line cleaning there will be loss of production due to shut down.

3. THERMAL SPALLING FOR DECOKING

To remove the deposited coke from inside the tube spalling of heater is done. The charge in the heater is reduced and steam is supplied along with boiler feed water. The sudded heating of the boiler feed water creates the turbulent flow and shock which descales the tubes.

4. ONLINE PIGGING FOR DECOKING

To remove the hard cokes heater is shutdown and a cleaning pig with metal bristells are passed inside heater tubes with some carrier fluid like water. The rubbing of bristles cleans the tube and decoke the heater.

5. BURNER MANAGEMENT PROGRAM

To avoid the flame impingement in the burner it is advisable to operate all the burners uniformly instead of firing 1 or 2 burners very high. A proper burner management program integrated with box temperature regulates the firing as per requirement to avoid flame impingements.

6. CONCLUSION

The furnace is inspected with the intention of finding out if the tubes were operating within the design temperature limits or not. The primary aim is to check whether the furnace tubes are coked or not. If it is coked decoking of the tubes during the shutdown is necessary. The assumption was that if there is coke, it must be in nearly the whole length of the tubes in all passes, because the only places where scales seemed not to be present is at the bottom of the tube. The areas at the bottom of the tubes were inspected. Patterns indicating coke were found in many places, and in the other places the temperature indicated that there was coke all the way down below the area that was viewable.

Comparing the calculated temperature inside with the measured temperature outside, the causes of temperature difference cannot be identified. An assumption is made that the steel should not be contributing too much, say not more than a difference of 50K. The remaining temperature difference comes from a combination of resistance of the scale and the coke.

Safety is covered by showing what patterns are caused by scaling, coking and flame impingement. In short, a furnace with scale is inefficient, one with coke is inefficient and dangerous, and flame impingement causes coking to take place. Decoking was not deemed necessary strictly from a safety stand point, the tube were not overheated. It was estimated that doing only descaling at this outage would reduce the thermal resistance by about one third, which would be a significant improvement.

ACKNOWLEDGEMENT

First and foremost, we express our heartfelt gratitude to our external guide, Er. Ankur K. Mishra, Assistant Manager-Inspection, BPCL-KR, for his valuable guidance, support and encouragement during the course of the project work and in the preparation of the report. We have greatly benefited from his experience and knowledge.

The help extended by all other staff members of the BPCL-KR are remembered with gratitude.

The constant encouragement and timely support rendered by our internal guide Er. Sivasubramanian P. Assistant professor, Saintgits College of Engineering, Kottayam is deeply remembered.

We thankfully acknowledge the principal, Dr.M.D Mathew Saintgits College of Engineering, Kottayam for giving us an opportunity to do this work.

We also remember with thanks to all our friends and well-wishers for their encouragement and support.

Above all, we would like to express our profound gratitude to God Almighty for His immense blessings upon us that led to the successful completion of this project work.

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