Reliability analysis on a shell and tube heat exchanger

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Abstract. A shell and tube heat exchanger reliability was done in this study using past history data from a carbon black manufacturing plant. The heat exchanger reliability study is vital in all related industries as inappropriate maintenance and operation of the heat exchanger will lead to major Process Safety Events (PSE) and loss of production. The overall heat exchanger coefficient/effectiveness (U_o) and Mean Time between Failures (MTBF) were analyzed and calculated. The Aspen and down time data was taken from a typical carbon black shell and tube heat exchanger manufacturing plant. As a result of the U_o calculated and analyzed, it was observed that the U_o declined over a period caused by severe fouling and heat exchanger limitation. This limitation also requires further burn out period which leads to loss of production. The MTBF calculated is 649.35 hours which is very low compared to the standard 6000 hours for the good operation of shell and tube heat exchanger. The guidelines on heat exchanger repair, preventive and predictive maintenance was identified and highlighted for better heat exchanger inspection and repair in the future. The fouling of heat exchanger and the production loss will be continuous if proper heat exchanger operation and repair using standard operating procedure is not followed.

1. Introduction
A shell and tube heat exchanger is used to transfer heat source from one stream to another to optimize energy and cost in a plant. It is the latent heat from a condensing vapor stream which is transferred to a colder stream in order to heat it. The unit may also function as heat exchange between the two streams without necessary phase change. In this case, the hot stream has to be connected to the shell side of the heat exchanger [1]. A shell and tube heat exchanger can also be used to transfer the heat from an evaporating liquid stream, which is typically water to the tube side stream.

As far as fouling is concern, a typical shell and tube heat exchanger is more likely to foul or corrode on the tube side when higher pressure is exerted. The deposition of unwanted particles or substance on heat transfer surfaces is called fouling. Fouling significantly impacts the mechanical and thermal performance of heat exchangers. Fouling is also known to be a dynamic phenomenon which changes over a period of time. Cleaning inside a tube is easier than cleaning the outside [2].

When a vapor or gas is used as a heat exchange stream, it is typically introduced on the shell side to allow the highest temperature difference (calculated as log mean temperature difference)
between the hot and cold streams. As for liquids with high viscosity, the pressure drop of the liquid flow through the tubes will be prohibitively large. Thus, liquids with high viscosity can be channeled on the shell side [3].

The most common material of construction of a typical shell and tube heat exchanger is carbon steel. Other materials such as stainless steel or copper are used when needed, and the choice is made by corrosion concerns as well as the mechanical strength requirements. Expansion joints are used to accommodate differential thermal expansion of dissimilar materials used. Fouling changes expansion rate of expansion joints by reducing total heat transferred [4].

In a carbon black petrochemical plant, the shell and tube heat exchanger (air preheater in Figure 1) is used to preheat air (in shell side) to temperature between 650 and 700°C for the combustion to produce carbon black which runs 24 hours daily. The combustion air heat exchanger is the primary means of direct energy recycle in carbon black production accounting for about 5% of the total energy needed. Carbon black heat exchangers are designed to use both radiation and convection to transfer heat. The heat exchanger is one of the critical equipment in the carbon black production operation as it is high in costs. Of late, the heat exchanger was found to perform below design capacity causing loss of product yield. The problem is that air cannot be heated to the set temperature, giving indication of severe fouling on the tube side (product from furnace in gas form and solid particles) thus requiring a lot forced and unplanned shut down to clear the fouling. Furthermore, there were incidents of temperature excursions due to heat exchanger fire (in tube side) because of the presence of excess oxygen from the carbon black production furnace. If the fire was significant, it could cause heat exchanger damage and worst if ruptured.

Therefore, the objective of the present work is to evaluate the performance parameters of a shell and tube heat exchanger through Aspen Plus® data history analysis by analyzing overall heat transfer coefficient and mean time before failure (MTBF). From this evaluation guidelines for heat exchanger inspections and repair were proposed for future use.

2. Methodology

2.1. Unit operation

The study will be based on a shell and tube heat exchanger in a Carbon Black Manufacturing Plant as in Figure 2. Cold Low Pressurized Air flow in and out the shell side named Cold LPA in and Cold LPA out, respectively. The set temperatures for the air were 100 and 650°C for inlet and outlet, respectively. Meanwhile, the products from the reactor for carbon black production at 850°C named Hot LPA In was fed into the tube side to heat the air, and flowed out at 648°C named as Hot LPA Out.

![Figure 2: A typical carbon Black Plant Heat Exchanger Operation](image)
Figure 1: Typical process flow diagram of a carbon black production using oil furnace method.
2.2. Calculation of overall heat transfer coefficient ($U_o$)

Figure 3 shows the flow of $U_o$ determination using the basis of Equation 1 and data from Aspen (Figure 4). It should be noted that this method only accounts for conduction within materials and does not take into account heat transfer through methods such as radiation (Perry, 1973).

\[ Q = U_o A \Delta T_{lm} \]  

(1)

Where $Q$ is total heat transferred (kJ), $U_o$ is overall heat transfer coefficient (kJ/m²°C), $A$ is total surface area (m²) and $\Delta T_{lm}$ is log mean temp difference. The $\Delta T_{lm}$ is calculated using Equation 2.

\[ \Delta T_{lm} = \frac{(\Delta T_1 - \Delta T_2)}{\log \left( \frac{\Delta T_1}{\Delta T_2} \right)} \]  

(2)

where $\Delta T_1 = T_1 - t_2$ and $\Delta T_2 = T_2 - t_1$. $T_1$ is inlet temperature of the shell-side (or hot) fluid, $T_2$ is exit temperature of the shell-side (or hot) fluid, $t_1$ is inlet temperature of the tube-side (or cold) fluid and $t_2$ is the exit temperature of the tube-side (or cold) fluid.

2.3. Mean Time between Failure (MTBF) Calculations

Reliability is the probability of the equipment or process functioning without failure when operated as prescribed for a given interval of time under stated conditions. Long failure free periods result in increased productivity. Thus, fewer spare parts are needed to be stocked and less manpower employed in maintenance activities hence lowering the costs. Increased availability, decreased down time, smaller maintenance costs and lower secondary expenditure result in a bigger profit. Setting reliability requirements is a corner stone of any reliability strategy. The reliability requirements have a quantitative part and that is mean time between failures (MTBF). MTBF is specified for a component and systems whose failures are characterized by a constant hazard rate [5].
Ideally the failure rate (FR) parameters should be determined on the basis of observations for the specific component types. Consequently, the failure rate parameters are determined on the basis of general experiences, both with the precursors of the relevant type and with the component types in general industrial applications. The parts count method is a technique for developing an estimate or prediction of the average life of the Mean Time between Failures (MTBF) of an assembly. It is a prediction process whereby a numerical estimate is made on the ability with respect to failure of a design to perform its intended function. Once the failure rate is determined, MTBF is easily calculated as the inverse of the failure rate as in Equation 3 [6]. The failure rate was analyzed for the 1 year time frame from January 2011 to December 2011.

\[ MTBF = \frac{1}{FR_1 + FR_2 + FR_3 + ... + FR_n} \] (3)

2.4.Highlights of Temperature Excursions to Determine A Heat Exchanger Fire

Figure 5 shows live Aspen data and a possible heat exchanger fire can be seen. The sudden temperature excursion in heat exchanger outlet temperature (colored pink) indicates fire in heat exchanger tubes which could lead to significant catastrophic process safety event. The sample data below shows the burner inlet temperature shot from 530 to 597°C during start up.

3. Results and Discussions

3.1. Overall Heat Transfer Coefficient (Uo) Analysis

Overall heat transfer coefficient represents how fast energy can be transferred between two points. It is related to the total thermal resistance between the two points. The resistance to heat transfer between the two fluids takes place in three steps: (1) resistance between the hot fluid and the tube wall, (2) resistance within the tube wall, and (3) resistance between the tube wall and the cold fluid. This causes loss in yield and the volume of the carbon black produced.
Figure 6 shows the overall heat exchanger coefficient ($U_o$) for the year 2011 starting from month of February until December. There was no data for the month of March, June, October, November and December due to maintenance activity and planned curtailing. On the 3rd February, the $U_o$ was calculated to be 99 kJ/m$^2$°C. It was found that on 6th February, the $U_o$ had dropped to 95 kJ/m$^2$°C. For example, on February 3rd, the log mean temperature was 384°C with corresponding $U_o$ of 99 kJ/m$^2$°C. Meanwhile, on 6th February, the log mean temperature increased to 397°C gradually which reduced the $U_o$ of the shell and tube heat exchanger to 95 kJ/m$^2$°C. Over a period of 3 days, the heat exchanger $U_o$ dropped 4 kJ/m$^2$°C gradually according to the data observed from Aspen. The probable major contributor of this is caused by fouling as there were no upsets in the process and no changes in the operating parameters. The $U_o$ in April, May, July August and September also shows the decrease in $U_o$ gradually upon start-up of production and after a few days. Increase in fouling gradually coats the tubes with carbon black thus decrease the preheated air temperature for the production of carbon black.

Fouling is the resultant effect of deposition and removal of carbon black on a heat exchanger tube surface. The processes occurred simultaneously and depended on the operating conditions. Usually, the removal rates increased with increasing amounts of deposit whereas deposition rates were independent of the amount of deposit. In the case of a shell and tube heat exchanger, the changes are caused by deposits such as increase in flow velocity and surface roughness. In the application of constant combustion air temperature or constant heat transfer coefficient boundary conditions, the interface temperature decreases as deposits build up. This in return forces optimum desired temperature for combustion of carbon black production to be reduced [5].

Coking and polymerization is a major cause of fouling in the shell and tube of heat exchanger of a typical carbon black application which directly causes the log mean temperature to increase, thus reducing the heat transfer. The decomposition of organic products (in the products after reaction in reactor) can lead to the formation of very viscous tar or solid coke particles at high temperatures and polymerization involves the formation of undesirable organic sediments or polymers in the tube side. The coke particles and polymers formed in the heat exchanger grows to such a large size that they drop out of solution and deposit on the process equipment. Such deposits can be extremely tenacious and
may require burning off the deposit in a timely manner to return the heat exchanger to satisfactory operation [3].

Figure 6: $U_o$ value changes during production of carbon black

Figure 7 below shows bar graph on the impact of the hot stream outlet temperature on the $U_o$ of a heat exchanger. From the bar graph below, it is deduced that at a constant cold stream outlet temperature (air), the increase in the hot stream outlet temperature indicates the initial stage of fouling. Surface is conditioned in the initiation period. Rough surfaces encourage particulate deposition and provide a good chance for deposit sticking. After the initiation of fouling, the persistence of the roughness effects will be more a function of the deposit itself. Even smooth surfaces may become rough in due course due to scale formation, formation of corrosion products, or erosion [7].

Figure 7: Effect of hot stream outlet temperature on $U_o$. 
A simple way to monitor a heat transfer system is to plot the graph of outlet temperature versus time. Loss of heat transfer and subsequent charge outlet temperature decrease as a result of the low thermal conductivity of the fouling layer or layers which is generally lower than the thermal conductivity of the fluids or conduction wall. As a result of this lower thermal conductivity, the overall thermal resistance to heat transfer is increased and the effectiveness and thermal efficiency of heat exchangers are reduced [8].

In one unit at an oil refinery, in Homs, Syria, fouling led to a feed temperature decrease from 210°C to 170°C in a crude distillation unit. In order to bring the feed to the required temperature, the heat duty of the furnace may have to be increased with additional fuel required and resulting increased fuel cost [9]. Alternatively, the heat exchanger surface area may have to be increased with consequent additional installation and maintenance costs. The required excess surface area may vary between 10-50%, with an average around 35%, and the additional extra costs involved may add up to a staggering 2.5 to 3.0 times the initial purchase price of the heat exchangers [9].

With the onset of fouling and the consequent buildup of fouling layer or layers, the cross sectional area of tubes or flow channels is also reduced. In addition, increased surface roughness due to fouling will increase frictional resistance to flow. Such effects inevitably lead to an increase in the pressure drop across the heat exchanger, which is required to maintain the flow rate through the exchanger.

Figure 8 shows the declining of the $U_o$ after a period of time and the burn out required to clear the fouling on the heat exchanger. Burn out means removal of fouling on the tube side of the shell and tube heat exchanger by introducing oxygen and heat source to burn off the fouled particles. During this burn out period, production has to be stopped thus a shutdown is required. Figure 8 reveals that after every burn out event, there is inclination of the $U_o$.

This burn out is required approximately once in 3-4 weeks to maintain a high $U_o$. However, it is noticed that after every burn out event, the $U_o$ is higher but differs from one burn out event to another. This is due to the incomplete burn off period or interval. An incomplete burn off heat exchanger will have residues of fouled material on the tubes which will cause the lower $U_o$.

![Figure 8: Trend on $U_o$ and the fouling burn out interval](image)

3.2. Analysis on the Mean Time between Failures
The calculated MTBF of a shell and tube heat exchanger is 649.35 hours (0.9 month). This value is very much lower than the standard MTBF of a typical shell and tube heat exchanger in the industry.
The standard MTBF is 6000 hours interval. The MTBF is an important system parameter in systems where failure rate needs to be managed, in particular for safety reasons.

The MTBF appears frequently in the engineering design requirements, and governs frequency of required system maintenance and inspections. In special processes called renewal processes, where the time to recover from failure can be neglected and the likelihood of failure remains constant with respect to time, the failure rate is simply the multiplicative inverse of the MTBF [10].

MTBF and reliability are really all about failure. Every product ever made will eventually fail, but ideally, not within its service life. Reliability and MTBF calculations are used to determine the likelihood of failure. Many people will look at the MTBF of a product and make assumptions. For example, if an MTBF is 100,000 hours, one may think they have a long time before having to replace their product [10].

Service life is the time that a product is in service out in the field. The useful life of a product is the time after the device is broken in/burned-in and before the device starts to wear out. In order to have the maximum service life, a customer would want to ensure that the service life matches the useful life. In other words, it is a good idea to have the product burned in before put into service. This can prevent failures due to defective parts [11].

3.3. Determining Heat Exchanger Fires on Shell and Tube Exchanger

Figure 9 highlights the significant change in the heat exchanger hot stream outlet temperature. The figure shows the significant increase of the carbon black hot stream outlet temperature from 445 to 604.7°C. This sudden spike in the temperature indicates there was a fire in the heat exchanger tubes. It important to identify these heat exchanger fires and overcome before it becomes a process safety event.

Aspen trending can be used to troubleshoot this but it takes time. As the first line of barrier for preventing such heat exchanger fires will be to configure layers of alarm such as advisory high temperature, critical high temperature. Besides that, an emergency heat exchanger spray has to be installed in case of a heat exchanger fire. Unfortunately by introducing water during a heat exchanger fire can cause significant damage to the heat exchanger tubes. Thermal shock will happen which can cause distortion of the heat exchanger tubes.

Thermal shock arises when a solid at uniform temperature is suddenly brought in contact with a fluid at a different temperature. If the solid is small, it may be assumed that its temperature will remain uniform throughout the solid although it will change with time. In the presence of temperature differences within the solid, thermal stresses will arise, increasing in magnitude as the temperature gradient increases. Plastic deformation or fracture may result.

![Figure 9: Heat exchanger Hot Stream Outlet temperature](image-url)
4. Proposed Guidelines for Heat Exchanger Maintenance

Exceptional efforts should be made to save tubes since this will, in general terms, ultimately prolong the useful, rated service life of the vessel. A quick fix should be avoided in virtually all cases. The apparent time saved, in short term, will be unlikely to compensate for the degradation of the equipment so provoked. Even a quick fix needs to be correctly executed and can be optimized as a temporary repair such that later restoration can be carried out at a future, but not too distant, planned unit shutdown. It is always best to have a source of spare parts available for immediate repair of the problem. Since this is not always possible, it is the most likely reason to execute what has been called above the temporary repair.

4.1. Routine maintenance on heat exchanger pressure vessels

Air pre-heaters, which are pressure vessels in their own right, also form part of a pressure system. Their design and construction is made in accordance with pressure vessel codes and first installation is often required to be verified by the local, national authorities. This verification is frequently made on the basis of the entire system: changes to which could invalidate the original approval notwithstanding any name plate rating.

The standard pressures which are normally requested by clients usually mean that the more onerous requirements of pressure vessel inspections and repair procedures are not compulsory or mandatory though they may apply to some of the higher-pressure exceptions which exist at some facilities. It is good and recommended practice that the repair procedures and maintenance records be carried out and kept as though the vessels were required to meet more stringent statutory requirements. There is a legal requirement to implement an appropriate maintenance regime on all plant and keep sufficient records.

4.2. Preventive and predictive maintenance

Like all major items of plant, heat exchangers are best subject to a schedule of preventive maintenance tasks. Some of these are properly part of operator care philosophies. These include all operational personnel. Many data are collected in the Distributed Control System (DCS) and Aspen systems. It is good practice to walk the site once a shift at least. Look for anything which is damaged as it may just be loose insulation. A maintenance work order is usually issued to execute a repair.

A pressure test with air is probably the easiest and most reliable test which can be carried out on a heat exchanger. It is recommended that the vessel be cleaned first. It is often useful to test the hot air duct at the same time so a blind flange mounted at the burner position is usually sufficient. There is no need to specify a flange on the nozzle of the heat exchanger simply for pressure testing. The easiest, quickest and surest way to not to over-pressure the system is usually to use the standby blower. It is not necessary to reach the operating pressure, if this is impossible, since this is not a certification test. As for inspection, verification and evaluation work it must be done as early as possible in the turnaround. It is no use carrying out the cleaning and pressure test in the closing days of the turnaround.

5. Conclusion

Uₜ declines after a few days of operations and continues to decline further till a shutdown takes place to burn off the fouling coke on the tube side of the heat exchanger. This happens in a cycle of 2 to 3 weeks depending on the severity of the fouled heat exchanger. The coke particles and polymers formed in the heat exchanger grow to such a large size that they drop out of solution and deposit on the process equipment. Such deposits can be extremely tenacious and may require burning off the deposit in a timely manner to return the heat exchanger to satisfactory operation. The calculated MTBF of a heat exchanger was 649.35 hours (0.9 month) which is significantly low than the standard MTBF of 6000 hours interval led to major loss of yield and production volume to the carbon black industry. The heat exchanger repair guidelines and robust standard operating procedures are vital in day to day plant
operation. These guidelines spell out the critical operating envelope and detailed repair methods technically to ensure the reliability and operability of the shell and tube heat exchanger.

References

[1] Suzuki K, Hiral K. and Miyake E 1998 *Int. J. Heat Mass Tran* 28 (4) pp 823-36.
[2] Manglik R and Bergles A 2008 *Exp. Fluid Sci.* 10 pp 171-80.
[3] Serth R. and Lestina T 2014 *Process Heat Transfer, Second Edition: Principles, Applications and Rules of Thumb.* (Oxford: Academic Press)
[4] Patiño D, Crespo B, Míguez JL 2016 *Appl. Therm. Eng.* 100 pp 849-860
[5] Jiang W, Gong J, Chen H and Tu S 2008 *Int. J. Pres. Ves. Pip.* 85 pp 569-74.
[6] Arsenyeva O, Tovazhnyansky L, Kapustenko P and Khavin G 2013 *Chem. Eng. Trans.* 18 pp 791-96.
[7] Zubair S and Shah R 2001 Fouling in Plate-and-Frame Heat Exchangers and Cleaning Strategies *Proc. Compact Heat Exchangers and Enhancement Technology for the Process Industries* eds R K Shah, A Deakin, H Honda and T M Rudy (New York: Begell House) pp 553–65.
[8] Bryan Research and Engineering Inc. 1997 *Cause of Edmeston Heat Exchanger Failure: Unit 2 Altamira.* 1998.
[9] Awad M, Abd El-Samad S, Gad H and Asfour F 2007 *Mansoura Eng. J.* 32 (1) pp 27-37.
[10] Thulukkanam, K 2013 *Heat Exchanger Design Handbook, Second Edition (Mechanical Engineering)* (Boca Raton: CRC Press)
[11] Lin S, Fan L, Azer N 1978 Augmentation of Single Phase Convective Heat Transfer with In-Line Static Mixers *Proc. Of the 1978 Heat Transfer and Fluid Mechanic Institute* ed C T Crowe, W L Grosshandler (Pulmann, Standford University Press).