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Failure Analysis of Tube and Shell Heat Exchanger

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***Abstract:** This paper will present an over view on the different types failures occurring in heat exchangers and the maintenance procedure adopted for smooth operation of the heat exchanger. Heat exchanger is present as a static equipment at Hindustan Organic Chemicals Limited. The operation of this heat exchanger involves the production of Phenol from TAR COLUMN. The case study deals with the failure analysis of heat exchanger in which its design is checked. In HOCL, a shell and tube heat exchanger is used in the production line of phenol. Hot oil at 328°C and 10.5 kg/cm2 is passing through the exchanger tubes. SS316 material is used in the tubes. 120 tubes at the top of the heat exchanger fails regularly and hence the plant have to be closed down for at least 2 days on each failure. The failure causes loss of hot oil (therminol) which cost approximately Rs 850 per litre. About 1cm drop in oil level costs about 5 lakhs. In order to overcome this problem, the design of this heat exchanger is analysed for finding out the reason behind this failure.*
***Keywords:** Heat, Tube, Shell, Exchanger, Failure.*

I. INTRODUCTION

Heat exchanger may be defined as equipment which transfers the energy from a hot fluid to a cold fluid with maximum rate and minimum investment and running cost. It is used to reduce temperature of one process fluid, which is desirable cool ,by transferring heat to another fluid which is desirable to heat without inter mixing the fluid or changing the physical state of the fluid. Heating is a vital operation in the petroleum and chemical refinery. Hence failure of a heat exchanger result ineffective transfer of energy. Normal operation of heat exchanger usually requires little operator attention .However, operating life of a heat exchanger can be drastically curtailed by improper start up and shut down practices. So properly planed executed maintenance schedule is indispensable for many industries having heat exchangers as a main equipment in their process plant. A detailed maintenance schedule of plant and machinery of an industry involves mainly monitoring without disturbing the operation of the plant as a whole.

II. PROBLEM DEFINITION

In HOCL a shell and tube heat exchanger is used in the production line of phenol. Hot oil at 328°C and 10.5 kg/cm^2 is passing through the exchanger tubes.SS316 material is used in the tubes. 120 tubes at the top of the heat exchanger fails regularly and hence the plant have to be closed down for at least 2 days on each failure. The failure causes loss of hot oil (therminol) which cost approximately Rs 850 per litre. About 1cm drop in oil level costs about 5 lakhs.

III. OPERATION OF HEAT EXCHANGER

Normal operation of heat exchangers usually requires little operator attention. However, operating life of a heat exchanger can be drastically curtailed by improper start up and shut down practices. Some common problems are:

A. Tube failure due to 'water hammer' effect caused by opening the shell inlet valve too quickly.
B. Bending of the pass partition plate in the partition channel due to slung flow from the tube inlet nozzle caused by rapid opening of the channel inlet valve.
C. Introduction of tube side fluid in a fixed tube sheet heat exchanger with the shell side empty (since the resulting change in the tube metal temperature may over stress the tube to tube sheet joint resulting in the failure).
D. Thermal stress induced cracking of thick sections in region of gross structural discontinuity, such as tube sheet / channel junction in integral design, due to rapid changes in the fluid temperature. In order to avoid such problems start up and shut down of the equipments should be carried out in a manner consistent with the original design basis.

At times, heat exchangers are designed to operate under differential pressure. The shell and the tube side pressure are always present simultaneously. The operator should ensure that the design assumption of differential pressure is never violated including the period of start up and shut down, or the period of system pressure testing.
Other operational problems in heat exchanger are flow induced vibration, rapid tube failure, corrosion and erosion of the tube wall, tube joint failure, fluid level control difficulties and flanged joint leakage.

IV. MAINTENANCE OF HEAT EXCHANGERS

Operating problems in heat exchangers may be broadly classified into three groups.

A. Structural Problems

Structural problems are the most serious; failure is often swift and irreversible. Failures caused by flow - induced vibration of heat exchanger tubes over shadow all other structural failures. Tube to tube sheet joints failure is also a frequent operational problem.

The other type of structural failure encountered in heat exchanger operation is leakage from bolted joints. Leaks frequently occur in nozzle flanges due to moment loading of the joint caused by thermal expansion of the interconnecting piping. In some cases, non-temperature distribution in the tube sheet or cover in multiple pass design induces joint leakage. Replacement of the leaking gaskets with one having more appropriate loading and relaxation properties is usually the panacea for such structural problems.

B. Performance Problems

The excessive tube fouling usually causes performance problems. In a heat exchanger during normal operations the tube surface gets covered by deposits of ash, soot, and dirt and scale etc. This phenomenon of rust formation and deposition of fluid impurity is called fouling. Deposition of foul ants on the inside of the tube surface reduces the available flow area and increase the skin friction, causing an increase in pressure loss and decrease in heat transfer. Uneven rates of fouling of tubes usually occur in units with low flow velocity design. Uneven fouling may occur on the shell side of the tubes due to a poor baffling scheme which leads to a flow misdistribution. Highly non-uniform fouling on severely modifies the metal temperature profile in some tubes resulting in large tubes to tube sheet joint leads. Thermal stresses in the internal of the heat exchanger can cause serious degradation of heat duty. The most obvious example is failure of welds joining pass partition plates to each other and to the channel.

C. Metallurgical problems

Stress corrosion, galvanic corrosion, and erosion are the most frequently reported metallurgical problems. Care in the selection of material can eliminate most of these problems where the galvanic action cannot be completely eliminated. The use of waster anode is recommended.

V. TYPES OF FAILURES

Various types of failures occurring in the heat exchangers are as follows:

A. Stress Corrosion Cracking

Stress corrosion cracking is a failure mechanism that is caused by environment, susceptible material, and tensile stress. Temperature is a significant environmental factor affecting cracking. For stress corrosion cracking to occur, all three conditions must be met simultaneously. The component needs to be in a particular crack promoting environment, the component must be made of a susceptible material, and there must be tensile stresses above some minimum threshold value. An externally applied load is not required as the tensile stresses may be due to residual stresses in the material. The threshold stresses are commonly below the yield stress of the material. Aluminum and stainless steel are well known for stress corrosion cracking problems. However, all metals are susceptible to stress corrosion cracking in the right environment.

B. Wear Failures

Wear may be defined as damage to a solid surface caused by the removal or displacement of material by the mechanical action of a contacting solid, liquid, or gas. It may cause significant surface damage and the damage is usually thought of as gradual deterioration. While the terminology of wear is unresolved, the following categories are commonly used.

1) *Adhesive wear*: Adhesive wear has been commonly identified by the terms galling or seizing.
2) *Abrasive wear*: Abrasive wear, or abrasion, is caused by the displacement of material from a solid surface due to hard particles or protuberances sliding along the surface.
3) *Erosive wear:* Erosion, or erosive wear, is the loss of material from a solid surface due to relative motion in contact with a fluid that contains solid particles. More than one mechanism can be responsible for the wear observed on a particular part.

C. Pitting Corrosion

Pitting is a localized form of corrosive attack. Pitting corrosion is typified by the formation of holes or pits on the metal surface. Pitting can cause failure due to perforation while the total corrosion, as measured by weight loss, might be rather minimal. The rate of penetration may be 10 to 100 times that by general corrosion. Pits may be rather small and difficult to detect. In some cases pits may be masked due to general corrosion. Pitting may take some time to initiate and develop to an easily viewable size.

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Pitting occurs more readily in a stagnant environment. The aggressiveness of the corrodent will affect the rate of pitting. Some methods for reducing the effects of pitting corrosion are listed below:

1) Reduce the aggressiveness of the environment
2) Use more pitting resistant materials

D. Uniform Corrosion

Uniform or general corrosion is typified by the rusting of steel. Other examples of uniform corrosion are the tarnishing of silver or the green patina associated with the corrosion of copper. General corrosion is rather predictable. The life of components can be estimated based on relatively simple immersion test results. Allowance for general corrosion is relatively simple and commonly employed when designing a component for a known environment. Some common methods used to prevent or reduce general corrosion are listed below:

1) Coatings
2) Inhibitors
3) Cathodic protection
4) Proper materials selection

E. Fatigue failure

Metal fatigue is caused by repeated cycling of the load. It is a progressive localized damage due to fluctuating stresses and strains on the material. Metal fatigue cracks initiate and propagate in regions where the strain is most severe.

VI. CAUSES OF FAILURE

A. Vibration

Damage from the tube vibration has become an increasing phenomenon as heat exchanger sizes and quantities of flow have increased .The shell side flow baffle configuration and unsupported tube span are of prime consideration mechanism of tube vibration.

B. Corrosion

High temperature in the system can cause oxidation due to it corrosion occurs. Chemical reactions of hydrocarbon can also causes corrosion.

C. Overheating of 120 tubes at the top

In the shell and tube heat exchanger at the inlet (bottom of the shell) hydrocarbon is in liquid state. The inlet temperature of hydrocarbon is 217°c and outlet temperature is 229°c. The heating fluid hot oil called Therminol passes through the tubes. The inlet of hot oil is at top of the bundle and outlet is at the bottom. The inlet temperature of the hot oil is 320 °c. and the outlet temperature is 270°c. If there is any obstruction or processing delay in the production line it causes the shortage of hydrocarbon supply in to the heat exchanger. During when the hot oil will be passed through the tubes and this converts the top hydrocarbon in bundle to vapour state. In the vapour state convective heat transfer (h) is less. This causes the top 120 tube become overheat.

VII. DESIGN ANALYSIS

A. Constructional details

Inside diameter of the tube 'di’ = 14.83mm
Thickness of the tube = 4.22mm
Outside diameter of the tube 'do' = 19.05mm
Inside diameter of the shell = 934mm
Number of the tubes = 360
Number of the pass = 6

B. Details of hot oil

Dynamic viscosity = 0.2centi poise = $20*10^{-4}$NS/M^2
Density = 0.807kg/m^3
Thermal conductivity = 0.095kcal/hrn°c = 0.1108w/m°c
Specific heat = 3.3518kj/kg°c

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C. Details of aromatic hydrocarbons

Dynamic viscosity = 0.93centi poise = $93*10''^4$NS/M^2
Density = 0.820kg/m3
Thermal conductivity = 0.1kcal/hm°c = 0.1167w/m°c
Specific heat = 2.356kj/kg°c

D. Length of tube

Average length of the tube = 2408102/360 = 6689mm = 6.689m

E. Operating conditions

Mass flow rate of hot oil 'mh' = 66173Kg/hr = 66173/3600*120 = 0.153Kg/sec
One time oil passes 120 tubes.
Mass flow rate of aromatic hydro carbons 'm_c'' = 64708 Kg/hr = 17.98Kg/sec
Inlet temperature of hot oil 'Thi' = 320^0C
Out let temperature of hot oil 'tho' = 270^0C
Inlet temperature of aromatic hydro carbons 'T_{ci}' = 217°c
Outlet temperature of aromatic hydro carbons 'T_{co}' = 230°c

F. Calculations

Log mean temperature difference= (T1 - T2)/ln (AT1/AT2)
AT1 = T_h,-Tco = 320-230 =90°c
A T 2 = T_{h0}-Tci = =270-217 =53°c
LMTD = (90-53)/ln (90/53) = 69.87°c
The multi pass cross flow heat exchanger, LMTD = F*LMTD
Correction factor 'F' is find from heat transfer data book using Temperature ratio 'P' and Capacity ratio 'R'.
Temperature ratio 'P'= (Rise in temperature of the cold fluid) / (Difference in inlet temperature of the two fluids)
P = (T_Co-T_{ci})/ (T_ho-T_{ci}) = (230-217)/ (320-217) = 0.126
Capacity ratio 'R'= (Temperature drop of hot Fluid) / (Temperature drop of cold fluid)
R = (Tho-Thj)/ (T_{co}-T_ci) = (320-270)/(230-217) = 3.8
Correction factor from data book chart =1
LMTD =1*68.87 =68.87°c
Consider the flow inside the tube,
Reynolds number 'Re' = (4* rrih) / (3.14*di *dynamic viscosity)
= (4*0.153)/ (3.14*0.01483*20* $10 \sim^4$) = 6578.28
Reynolds number 'Re' greater than 2300 so flow is turbulent.
In case of turbulent flow, Nusset number ''Nu' = 0.0238*Re^{08} Pr^{04}
Prandtl number 'Pr' = (dynamic viscosity*specific heat)/(thermal conductivity of hot oil)
= ($20*10''^4 83.318*10^3$)/0.H08 = 59.89
Nu = 0.023*6571.28 ^{08}*59.89 $^{0 4}$ = 138.9
Convective heat transfer coefficient 'hi' = (Nu*k)/di = (138.69*0.1108)/0.01483 = 1036.2w/m^2k
Consider the flow over the tube,
The flow over the tube is due to natural convection.
Prandtl number 'Pr' = (dynamic viscosity*specific heat)/(thermal conductivity of aromatic hydro carbons)
= ($3* 10''^4*2.356*10^3$)/0.1167 = 188.13
Grashof number 'Gr = (L^3(Vgt)/v^2
Where, Length of the tube 'L'= 6.689m
V = volumetric expansion = l/T = 1/(295+273) = 1.760* $10''^3$k'''
Assume surface temp of tube is the mean temp of the hot oil 'T' = (320+270)/2=295°c
t = tube temp - fluid temp =295- ((230+217)/2) =71.5°c
v = dynamic viscosity/density = ($93*10''^4$)/0.820 = $11.34*10''^3 m^2/s$

$Gr = (6.089^3 * 0.00176 * 9.81 * 71.5)/(11.34*10^{'3)2} = 2.878*10^6$

$Gr*Pr = 2.87*10^6 * 188.18 = 0.539*10^9$

$Nu = 0.53(Gr*Pr)^{1/4}$ for $(10^4 < Gr*Pr > 10^9)$

$= 0.53(0.539*10^9 * 188.18)^{025} = 87.42$

$Nu = h_0 d_0/k$

$h_0 = (87.42*0.116)/(19.05*10\sim^3) = 494.74 w/m^2k$

Overall H. T. Coefficient,

U = 1/ ((do/ (di*hi)) + ((do/2k) In (do/di)) + (1/ho))

= 1/ ((0.0195/ (0.01483*1036.4)) + ((0.01905/2*13.6) In (0.01905/0.01483)) + (1/494.724))

$= 290.0599\ w/m^{2o}c$

Heat transfer rate for cold fluid,

$Q = m_c c_{pc} (T_{co}-T_{ci})$

Where, $m_c = 17.98$kg/sec, Cpc =2.356kj/kgoc, T_{co} =230°c, T_{ci} =217°c

Q =17.98*2.356*10 3*(230-217) = 550521.28w

Heat transfer rate for hot fluid,

$Q = m_h c_{ph} (T_{h0}-Thi)$

Where, $m_h = 0.153$kg/sec, Cph = 3.318kj/kg°c, T_{co} = 320°c, T_{ci} =270°c

$Q = 0.153*3.318*10^3*(320-270)$

Q = 120*25382.7.7w (one pass has 120 tubes)

= 3045924w

Q = U* A* LMTD

A = Q/ (U*LMTD)

Area required for the heat transfer = 3045924/ (290.05*69.87) = 150.1m^2

Actual area =3.14*do*L = 3.14*.01905*6.689*360

= 144.040m^2 Actual area =144.040m^2 *103%=148.36

Actual area < area required for the heat transfer .So, design is not safe.

VIII. CONCLUSION

The shell and tube heat exchanger present in HOCL is analyzed and from the analysis various reasons behind the failure of this heat exchanger are found. Vibrations developed in the equipment during its operation, corrosion of metals used in the equipment and overheating of the 120 tubes at the top are the major reasons behind the failure of this heat exchanger. Also, the entire design of this heat exchanger is checked and it is found that the actual area present in this heat exchanger is less than the area required for the heat transfer, which means the design of this heat exchanger is not safe.

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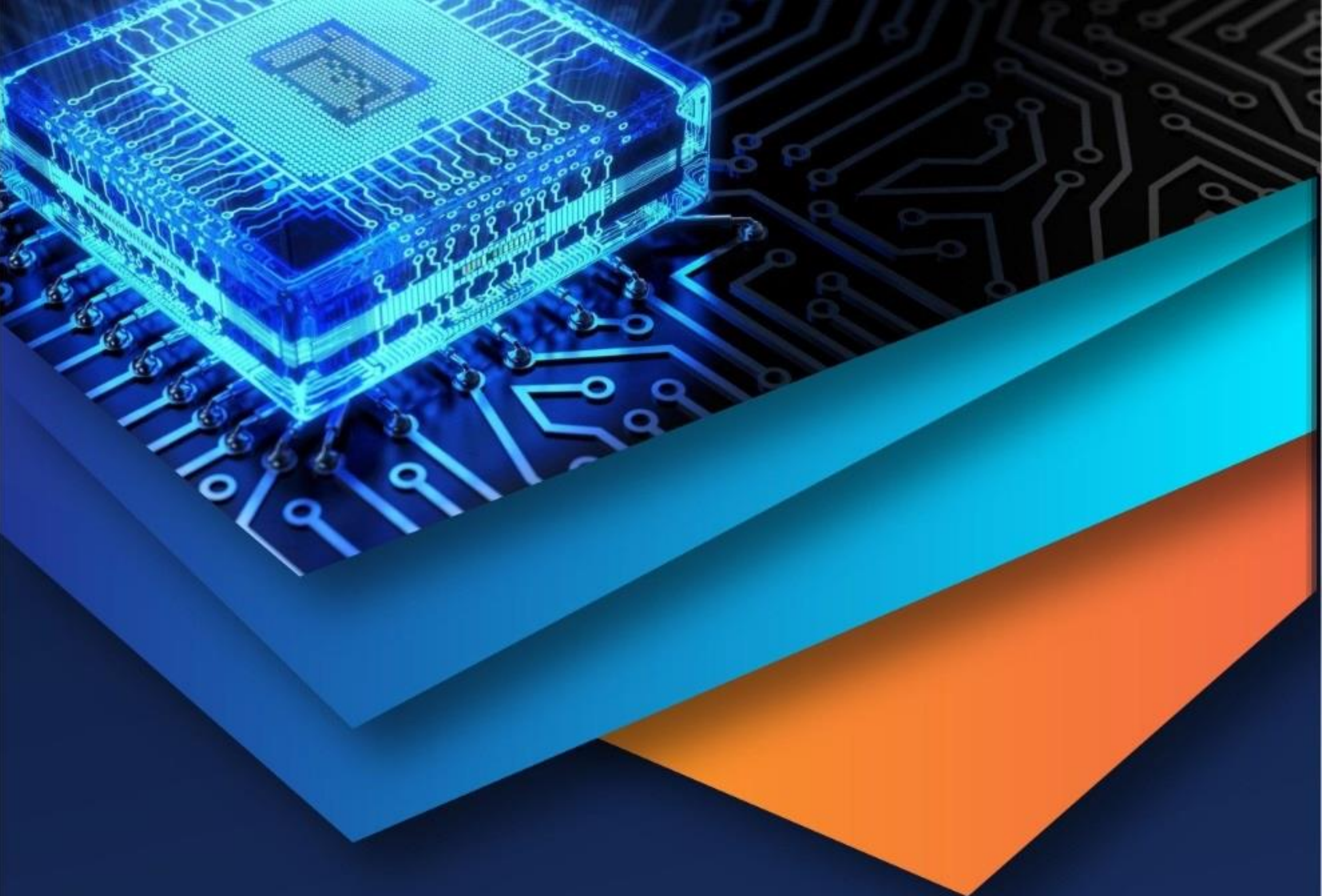

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