Analytical Study of Coke Drum Skirt Support Hot Box

Nirmal Pravin Chandra, S. B. Belkar

Abstract— ***Delayed coke drums are operated under severe conditions of cyclic heating and forced cooling that apply repetitive thermal stresses to the drum walls and the skirt. Since thermal cycling is most severe near the bottom of the coke drum, where temperatures can reach up to 1000°F, the skirt and other attachment welds are just as prone to cracking and premature structural failure as the vessel wall. The purpose is to determine a skirt / "Hot-box" junction geometry which will minimize thermal gradient stresses and improve fatigue life. The process flow of coke drum along with the temperature gradient due to coking process and the effect of thermal stresses on the skirt shell junction/ hot-box using finite element model. In present project work comparative analysis of hot box is done by analytical, FEA using ANSYS 13. Study demonstrates that by modifying the dimensions of the hot box such as length, will affects the fatigue life of coke drum. This appears to be due to the longer hot-box length, which results in a more gradual thermal gradient and also moves the gradient lower on the skirt away from the welded connection.***

Keywords: Coke drum, Hot box, fatigue life

I. INTRODUCTION

As the crude oil demand of the world constantly increases, extraction of heavier crude oils becomes more and more necessary. Also, higher fraction of the low-value residual oil needs to be converted into valuable hydrocarbon stocks (gasoline, Jet fuel, gas oils, lube oils, etc.). Therefore, the significance of the residue conversion technologies has been increasing in the past decade. These technologies can significantly enhance the conversion level of a petroleum refinery. The skirt junction fatigue life study starts with steady state thermal stress analysis followed by transient thermal stress evaluation using FEA method. Also an analytical study is performed to estimate the fatigue life estimation of shell to skirt junction/"hot-box". Drum is mounted on the skirt. Skirt and vessel are welded at the BTL (Bottom Tangent Line).Due to cyclic loading process, operation in the drum cause cyclic loading at this weld junction, which in turn cause fatigue failure Delayed coking is one of the most wide-spread residue conversion technologies. It is a thermal cracking process used in petroleum refineries to upgrade and convert petroleum residuum (bottoms from atmospheric and vacuum distillation of crude oil) into liquid and gas product streams leaving behind a solid concentrated carbon material, petroleum coke. In particular, welded skirt supports of the type commonly used in vertical pressurized reactors are often subject to fatigue failure. The cycling causes abnormal transient thermal stresses in the vessel near these joints which tend to progressively weaken the structure.

II. LITERATURE REVIEW

J.W.Thomas. studied that during the last 10 years there has been a major switch from carbon-molybdenum to chrome molybdenum as a drum material as it gives better service for processing graphite coke. Marcos Sugaya Colin McGreavy The skirt and cone generally have more similar temperatures. The slower cooling rates and the gradients which develop in the conic section are caused by competition between the heat removed from the wall to the coke bed and heat supplied by the skirt attachment through the welded joint, as well as by radiation and convection. The form of the weld can also cause the heat which is retained in the skirt to move into the conic section which would explain why the shell cools faster than the conic section. The results indicate that the stresses that define the life of the skirt attachment weld on a fatigue basis are mainly established during warm-up or perhaps shortly after switching on. The inversion of stresses observed during the cooling operation at the outer region is mild and does not seem to be significant as far as fatigue assessment is concerned. Richard Conticello, Tej Chadda (2007)With coke drum diameters increasing in size to 30 feet and higher combined with shorter coking cycles, there are additional process and thermal factors that require development of a fatigue resistant coke drum design including a skirt junction/hot-box and support system. Since the coke drums undergo a severe transient heat-up/cool-down cycle and thermal gradient during each fill and decoking cycle, fatigue resistant design of 30 feet and larger size coke drums is critical to minimize the thermal/fatigue damage mechanism including cracking and bulges of drum shell, cracking of support skirt to drum shell junction, failure and/or distortion of anchor bolts, concrete, and overhead piping and nozzles.

III. OBJECTIVES

- To determine the fatigue life of the coke drum skirt support for design conditions by using Finite Element Analysis in accordance to ASME Boiler and Pressure Vessel code section VIII Div.2
- The main focus is to select the optimum geometry of skirt junction/Hot-box is used for the final design.
- The analytical procedure is followed by finite element analysis and the fatigue of skirt is calculated.

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IV. MATERIAL

The material of construction for shell, head, toricone and skirt shell is SA 387 GR.11 CL2 Material properties used for the analysis are given in table 1Insulation material considered in FEA is cellular glass and its thermal conductivity is 0.068 W/m-k **Poison's ratio**: 0.3

Table 1. Material Properties for SA 387 GR.11 CL 2

Temperature	Young's Modulus E	Thermal Conductivity, k	Thermal Expansion Coefficient, α
^{o}C	GPa	W/m ^{o}C	Mm/mm/ ^{o}C
25	204	41	11.52E-06
100	200	40	12.11E-06
200	193	40.1	12.7E-06
300	186	38.7	13.23E-06
400	179	36.8	13.88E-06
500	169	34.8	14.34E-06

Table 2. Material Properties for Insulation and Fire Protection Material

	Thermal Conductivity K (W/m^{0}C)
Insulation	0.068
Fire Protection	1.395

Temperature Analysis

In this section, the temperature was performed in HOT and COLD conditions to obtain temperature distribution.
The analysis is performed using "ANSYS 13.0" general purpose FEA software

Loading and Boundary Conditions:

Cold condition

- **Design Basis:**

As per the process data for cold condition, design temperature for this case is 150 degree C and design pressure is 12.06 kg/cm2G has been set at the inside surface of the coke drum. Radiation is employed inside the hot box with emissivity 0.8 and Stefan Boltzmann constant 5.67 x 10-8 W/m2K4 . At the outside surface of the insulation, convective heat transfer coefficient of 10 W/ m2 K has been applied. Reference temperature 25 degree C

Hot Condition

- **Design Basis:**

As per the process data for Regeneration condition, temperature has been set at the inside surface of the coke drum but the design temperature of coke drum in this case is 504 degree C and design pressure is 9.93 kg/cm2G, hence as a conservative approach, 504 degree C is considered as a maximum temperature for this condition. Radiation is employed inside the hot box with emissivity 0.8 and Stefan Boltzmann constant 5.67 x 10-8 W/m2K4 . At the outside surface of the insulation, convective heat transfer coefficient of 10 W/ m2 K has been applied..
Calculation of outside heat transfer coefficient

$= h_{cv}=8.9*(V^{0.9})/(D_e^{0.1})$

………Refer ISO 12241

D_e is external insulation diameter, expressed in meter.
V is the air velocity, expressed in meters per second.
Assuming air velocity =1m/s,
hcv = 7.77 W/m^2 –K
≈ 10 W/m^2-K

Boundary Conditions

Symmetric boundry is applied at the axis of head.To avoid rigid motion of the model, top edge of shell is vertically constrained.

V.ANALYSIS

Geometrical and Mesh Model

Axisymmetric FE Model is considered for this analysis as the geometry and loading are symmetrical above the axis of roation. FE model consists of skirt toricone, shell and insulation. The details above the geometry are shown in fig.1. Mesh has been generated using Plane55 element for thermal analysis. PLANE55 used as a plane element or as an axisymmetric ring element with a 2-D thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node. Also PLANE 25 used for structural analysis The element is defined by four nodes having three degrees of freedom per node: translations in the nodal x, y, and z direction. For unrotated nodal coordinates, these directions correspond to the radial, axial, and tangential directions, respectively.

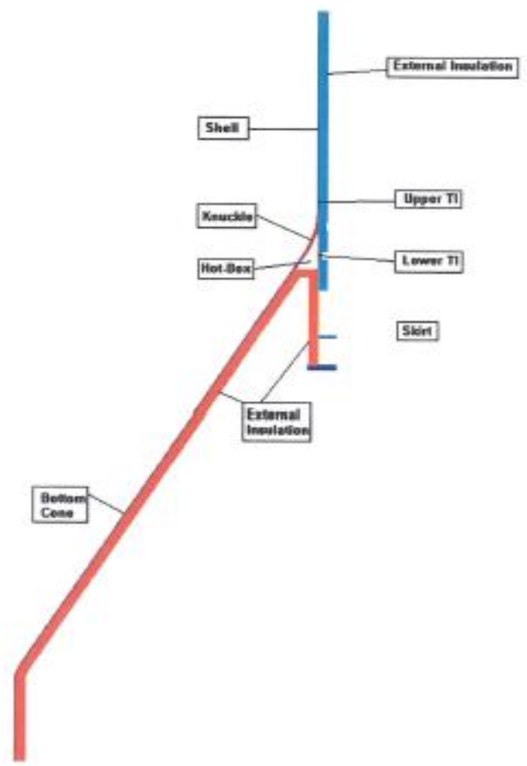

Fig. 1 Finite Element Model of Coke Drum Skirt/Knuckle/Shell Junction and Hot Box Detail

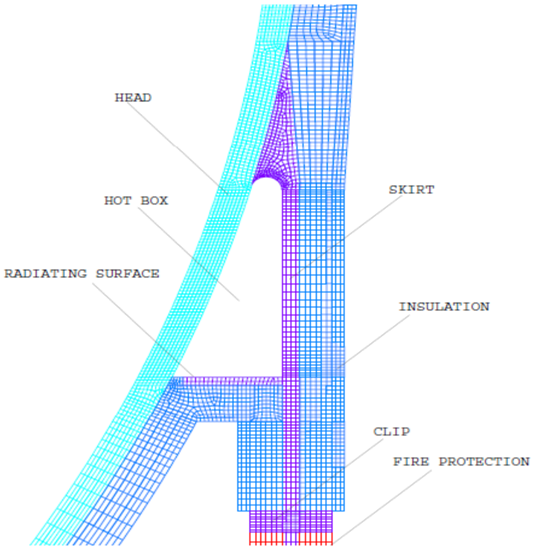

Fig. 2 FE Model for Thermal Analysis (Zoomed View Near Hot Box)

Fatigue Calculations

Analysis of hot box according to the length is done for two cases.

CASE: 1

- **Hot box length, L = 800mm**

The effective alternating equivalent stress amplitude:

$$S_{alt,k} = \frac{[K_f \cdot K_{e,K} \cdot (\Delta S_{P,K} - \Delta S_{LT,K}) + K_{V,K} \cdot \Delta S_{LT,K}]}{2}$$

Where,

$S_{alt,k}$=Alternating Equivalent Stress for kth cycle

Kf=Fatigue strength reduction factor of 1.2, as all welds are full penetration, full volumetric examination and surface will be examined with MT/PT and VT as per Table 5.12

Ke,k= Fatigue penalty factor=1.0 (as ΔSn,k<Sps)

Kv,k=Poission correction factor (Take as 0.5 based on conservative approach)

ΔSLT,k= Local thermal equivalent stress.

Alternating stresses is obtained from maximum Von Mises stress value of Mechanical and thermal stresses. Local thermal equivalent stress **(ΔS_{LT})** for length 800mm is shown in fig.3

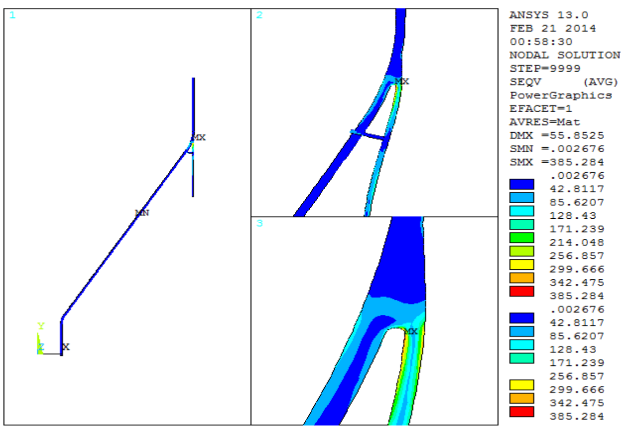

Fig.3 Differential Stress between HOT and COLD Condition (ΔS_{LT})

Range of primary plus secondary plus peak equivalent stress **(ΔS_{PS})** for length 800mm is shown in fig.4

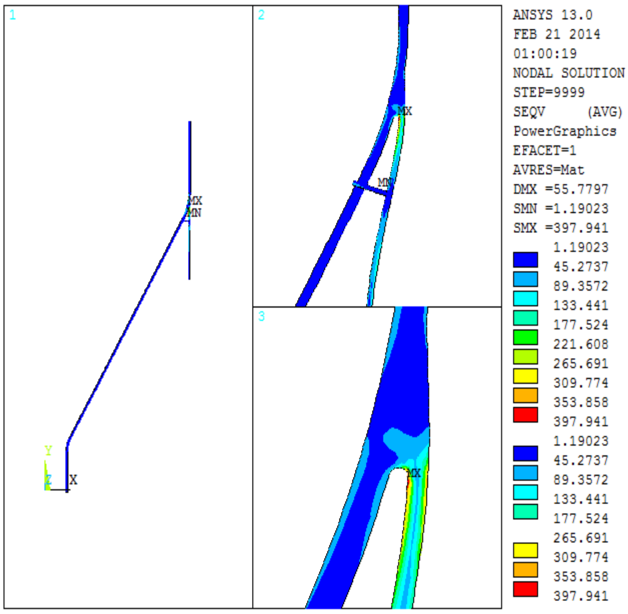

Fig.4 Differential Stress between Combine Loading for HOT and COLD Condition (ΔS_{PS})

Table 3.Analysis Results for $\Delta S_{p,k}$ and $\Delta S_{LT,k}$

	Shell, Toricone, Skirt
$\Delta S_{p,k}$	397.941
$\Delta S_{p,k}$ -$\Delta S_{LT,k}$ (MPa)	12.657
$\Delta S_{LT,k}$ (MPa)	385.284
Kf	1.2
S_{alt} (MPa)	103.915
E_T	186E+03
E_{fc} (MPa)	195E+03
N	3650
D_f	3.52E-03

Note: Cycles Df ≤ 1, hence the design is safe.

Where,

E_T = Modulus of elasticity of the material under evaluation at the average temperature of cycle being evaluated.

Efc = modulus of elasticity used to estimate the design fatigue curve.

N = Number of allowable design cycle.

Df = Fatigue damage

$$N = 10^X \cdot \left(\frac{E_T}{E_{FC}}\right)$$

where

$$X = \frac{C1 + C3\left(\frac{S_a}{C_{us}}\right) + C5\left(\frac{S_a}{C_{us}}\right)^2 + C7\left(\frac{S_a}{C_{us}}\right)^3 + C9\left(\frac{S_a}{C_{us}}\right)^4 + C11\left(\frac{S_a}{C_{us}}\right)^5}{1 + C2\left(\frac{S_a}{C_{us}}\right) + C4\left(\frac{S_a}{C_{us}}\right)^2 + C6\left(\frac{S_a}{C_{us}}\right)^3 + C8\left(\frac{S_a}{C_{us}}\right)^4 + C10\left(\frac{S_a}{C_{us}}\right)^5}$$

As the ultimate tensile strength for material SA 387 GR.11 CL 2 is 515 MPa, and the alternating stress value is less than 214 MPa, table 3.F.1 from ASME section VIII div.2 is used.

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Table 4 for (σ) *uts* ≤ 552*MPA* (80*ksi*)

Coefficients Ci	Shell, Toricone, skirt 48≤ Sa < 214 MPa
C1	2.254510E+00
C2	-4.642236E-01
C3	-8.312745E-01
C4	8.634660E-02
C5	2.020834E-01
C6	-6.940535E-03
C7	-2.079726E-02
C8	2.010235-04
C9	7.137717E-04
C10	0.0
C11	0.0

Fatigue evaluation has been done as per ASME Sec VIII Div.2, Part 5 and annexure 3F. Under the above fatigue loading conditions, the number of fatigue cycles are 1.03662E06 which are higher than the desired number of cycles 3650, hence the design is safe.

CASE: 2

- **Hot box length, L = 990mm**

Local thermal equivalent stress (ΔS_{LT}) for length 990 mm is shown in fig.5

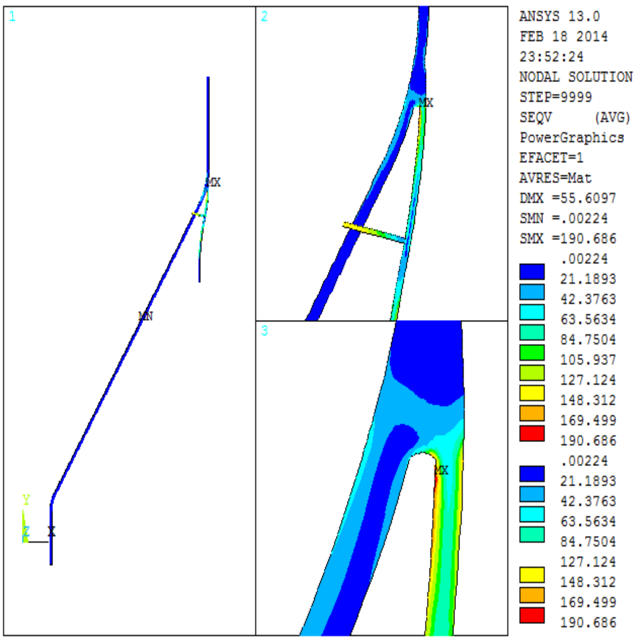

Fig.5 Differential stress between HOT and COLD condition (ΔS_{LT})

Range of primary plus secondary plus peak equivalent stress (ΔS_{PS}) for length 800mm is shown in fig.6

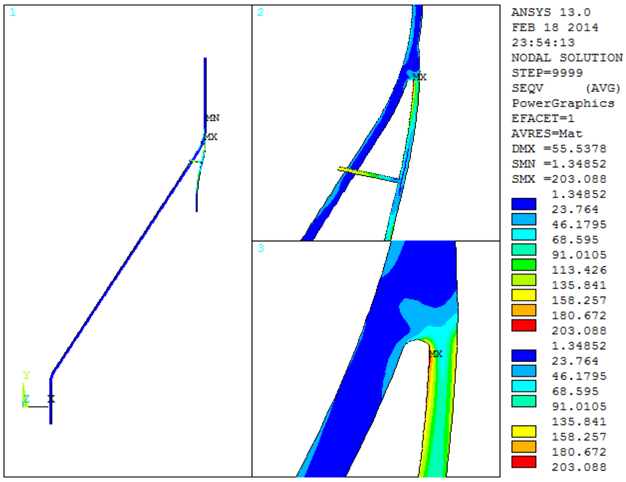

Fig.6 Differential Stress between Combine Loading for HOT and COLD Condition (ΔS_{PS})

Table 5.Analysis Results for $\Delta S_{p,k}$ and $\Delta S_{LT,k}$

	Shell, Toricone, Skirt
$\Delta S_{p,k}$	203.088
$\Delta S_{p,k}$ -$\Delta S_{LT,k}$ (MPa)	12.402
$\Delta S_{LT,k}$ (MPa)	190.686
Kf	1.2
S_{alt} (MPa)	55.1127
E_T	186E+03
E_{fc} (MPa)	195E+03
N	3650
D_f	1.228E-06

By using the same formulas and table as used in case 1 Fatigue evaluation has been done as per ASME Sec VIII Div.2, Part 5 and annexure 3F. Under the above fatigue loading conditions, the numbers of fatigue cycles are 2.9723E09 which are higher than the desired number of cycles 3650, hence the design is safe.

VI. RESULTS AND DISCUSSION

Overall results from above two cases are compaired in table 5.It can be observed from the comparison that as the length of the hot box increases, the value of alternating equivalent stress decreases and hence the fatigue life of the skirt support increases.

Table 6.Comparison of Result for Above Two Cases

	Shell, Toricone, Skirt	**Shell, Toricone, Skirt**
	Hot box length,L=800mm	Hot box length,L=990mm
$\Delta S_{p,k}$	397.941	203.088
$\Delta S_{p,k}$ -$\Delta S_{LT,k}$(MPa)	12.657	12.402
$\Delta S_{LT,k}$ (MPa)	385.284	190.686
Kf	1.2	1.2
S_{alt} (MPa)	103.915	55.1127
E_T	186E+03	186E+03

E_{fc} (MPa)	195E+03	195E+03
N	3650	3650
D_f	3.52E-03	1.228E-06

VII. CONCLUSION

1. Primary study for coke drum including operation principle of coke drum with various loading cases has been completed with modeling technique of finite element method.
2. Finite element analysis is used to evaluate the thermal and stress profiles for the COLD and HOT conditions.
3. It is observed that by modifying the dimensions of the hot box, alternating equivalent stresses decreases.
4. Reducing the length by 190mm minimizes 28% of fatigue life.
5. From the detail fatigue analysis, It is observed that hot box length is one of the most important factor which affects the life of coke drum

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