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STRUCTURAL ANALYSIS AND FATIGUE LIFE CALCULATION OF A COKE DRUM

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Abstract. Coke drums are pressure vessels utilized in Delayed Coking Units of oil refineries, which convert heavy fractions, like vacuum and atmospheric residues, into lighter product streams like gas oil, naphtha and gases. These equipments have a large history of problems, such as cracks and cumulative plastic deformations, due to the severity of the thermomechanical and cyclic loadings to which they are submitted. This work has as object of study a coke drum in operation, in which there are skin temperatures measurements. Through numerical analysis by Finite Element Method (FEM), it is possible to obtain the stress field in the region of the skirt to shell attachment and, from this field, the estimated fatigue life of the equipment. The main goal of this study is assessing the influence of thermal and operational parameters on the fatigue life of coke drums. Through the obtained results, a 50% reduction in the temperature gradient between the upper and intermediate regions of the skirt throughout the whole cycle increases the fatigue life of the coke drum by about 10%. Additionally, the reduction of 1°C in switch temperature reduces the fatigue life of the equipment by 0,9%.

Keywords: Coke drum, Finite Element Method, Fatigue.

1. INTRODUCTION

The Delayed Coking Units (DCU) have a large importance in oil processing because they convert heavy fractions into lighter products. Matusic (2008) has estimated a 50% participation of heavy oils in the global market at 2030.

The thermal cracking reactions in DCU occur inside the coke drums, which are considered to be mechanically critical due to the intensity of the process conditions to which they are subjected. The drums undergo fast and cyclical heating and cooling, becoming susceptible to thermal fatigue and to cumulative localized plastic deformations. Along the years of operation, many coke drums tend to develop bulges in the shell, and cracks may arise in several regions, like the skirt to shell attachment and near the bulges. These problems can occur relatively early in the operational life of these equipments.

The most important phases of coke drum cycle are: preheating, filling, cooling and decoking. The thermomechanical phenomena that occur in these equipments are very complex, like random thermal loading due to coking reactions that occur inside the equipment, pressurization, fast heating and cooling and cummulative plastic deformation in the shell. Because of this factors, several techniques of monitoring, inspection and repair have been developed and applied in the coke drums. These equipments have been object of research in the past years with the basic objective of developing better techniques of project, manufacturing and operation, reducing the failures and increasing its fatigue life.

Operational parameters such as pressure, feed temperature, preheating time or hot feed injection time, switch temperature (temperature of the equipment when the filling phase initiate), cycle duration, and others, determine the thermomechanical loading and the alternating stress acting on the equipment and, thus, influence on its fatigue life. Therefore, the goal of this work is to obtain the fatigue life of a coke drum pertaining to a PETROBRAS refinery, considering measured skin temperatures, the actual and original operating conditions and evaluate the influence of thermal and operational parameters on the fatigue life of coke drums.

2. LITERATURE REVIEW

According to a study accomplished by Oka, *et al.*, (2010a), the thermal stresses in eventual hot and cold spots in the shell during the cooling stage are sufficient to initiate bulges. According to Xia, *et al.*, (2010), the main cause of high stresses in the clad, which is the internal coating of the vessel, is the difference between the coefficients of thermal expansion of the base and clad materials. In the cooling phase, the external surface of the shell suffers a complete cycle of axial deformation, expanding and contracting. Oka, *et al.*, (2010b) have presented an exponential relationship between the number of design cycles and the hot feed injection time (wich is part of the preheating phase). This parameter is the main cause of high stresses in the skirt to shell attachment at the beginning of the filling phase, according to this authors. Marangone, *et al.*, (2010) have found a directly linear correlation between switch temperature and fatigue life of a coke drum. For a switch temperature of 150°C, the fatigue life would be of 3,679 cycles and for 300°C, it would be 11,817 cycles, in the case studied by these authors. A similar but exponential correlation was obtained by Oka, *et al.*, (2011). Temperature differences of 120°C between the shell and the skirt were observed and the upper end of the inner surface of the skirt was found to be the critical point of the vessel. The switch temperature has a strong relation to the stresses in the skirt to shell attachment, according to these authors. The work accomplished by Ju, *et al.*, (2011), indicates that the clad material suffers plastic shakedown in certain circumstances even under normal operating thermal and mechanical loadings of the coke drum. Cold and hot spots occurring at the same region of the shell induce progressive bulging and the cold spot can cause more severe local bending than the hot spot.

3. MATERIALS

The coke drum which is the object of this study, its geometry and the points of skin temperature measurements are indicated in Fig. 1. It is also possible to observe the region inside which there is no thermal insulation where the heat is transfered by natural convection and radiation between the bottom cover and the skirt, which is called hot box. Through 16 thermocouples installed at 4 elevations (3 at the shell, positions T2 to T4, and one at the upper region of the skirt of the equipment, T1), and measurements by a portable thermocouple at an intermediate point of the skirt (position T0), the skin temperatures of the equipment are obtained. From the fixed thermocouples, 5 subsequent cycles are registered and from the portable thermocouple, there are measurements during 3 periods of 3 different cycles, which complement each other to represent a complete cycle.
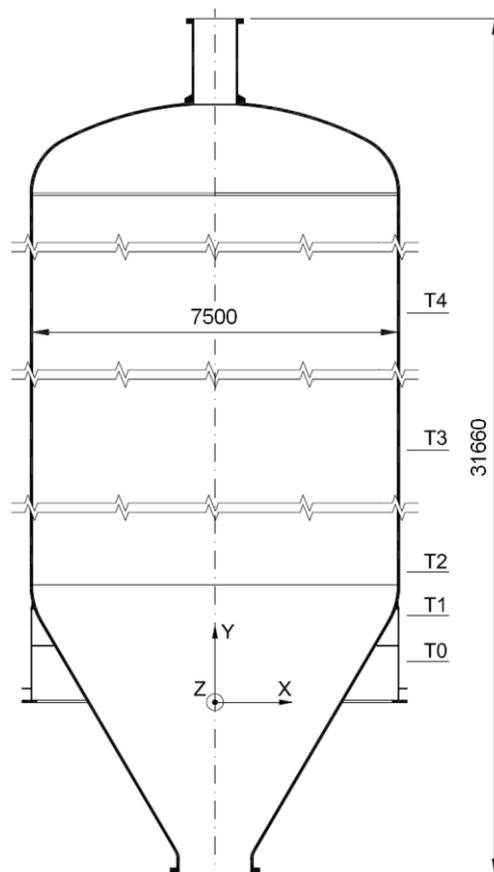

Figure 1. Coke drum main dimensions (mm) and points of skin temperature measurements.

4. METHODS

4.1 Approximation of temperatures and pressures via Fourier series

The temperatures obtained as described in the previous chapter are utilized in an optimization problem in which the objective function (D) is the sum of the squares of the differences between the temperatures obtained by an Fourier series ($T_{FS}(t_i)$) and the experimental ones ($T_{ex}(t_i)$), multiplied by the time interval between measurements (Δt_i) and divided by the total time (t_{tot}), presented in Eq. (1).

$$D = \frac{\sum_{i=1}^{n_e}(T_{FS}(t_i) - T_{ex}(t_i))^2 . \Delta t_i}{t_{tot}} . \qquad (1)$$

The number of points of an experimental data series is n_e and t_i are the time points in which the temperature measurements are recorded and used in the optimization problem. By minimizing this error function (via "fminsearch" subroutine of the software Matlab^{TM}), one can obtain the optimal parameters of the Fourier series that best represent the real temperature data. The same procedure is done with the experimental measurements of pressure. In the reference configuration 5 coeficients are utilized in the Fourier series.

4.2 Finite element model

The whole geometry of the equipment is represented in a two-dimensional model, with a mesh consisting of predominantly quadrilateral elements of 4 nodes and triangular elements of 3 nodes, with bilinear displacements and temperatures (both axisymmetric and thermally coupled). The mesh obtained through a refining process which verify the resulting stresses convergence has a total of 98,899 elements and 101,415 nodes. The mesh, in the region of the skirt to shell attachment, is shown in Fig. 2.
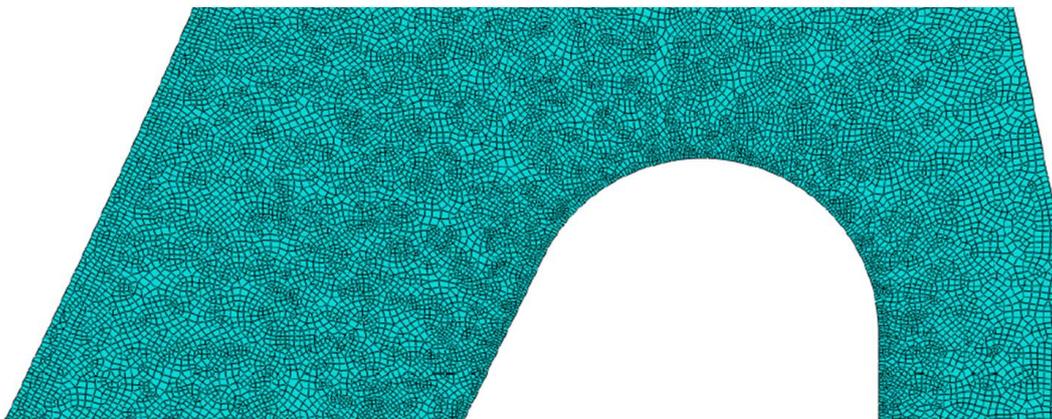

Figure 2. Finite element mesh of critical region of the coke drum model - part of the skirt(right) to shell(left) attachment.

All the loadings to which the equipment is subjected are represented in the model: dead weight of the vessel including insulation, internal pressure (whose variation is defined by a Fourier series), weight of the coke and hydrostatic pressure of the cooling water, both with linear variations according to the characteristics of the process.

The boundary conditions of the model are: axisymmetry condition, simple bear on the bottom surface of the support (skirt), and nodal temperatures defined throughout the whole geometry. The coke drum model is divided in five areas: the inferior and intermediate region of the skirt (where the temperatures are represented by T_{T0}), the upper region of the skirt (temperatures represented by T_{T1}), the bottom cover with the bottom region of the shell (T_{T2}), the intermediate region of the shell (T_{T3}) and the upper cover with the upper region of the shell (T_{T4}). The temperatures corresponding to the respective experimental measurements are specified at each region through Fourier series whose coefficients (input data of the model) are obtained by the optimization process described in the previous section.

From the stress fields obtained via FEM - software ABAQUS^{TM}, at approximately 1300 time points, the von Mises equivalent stress range and the alternating stress are obtained at the critical point located at the upper end of the inner surface of the skirt, through the procedure described in the next section. This point is indicated by the arrow in Fig. 3 which presents the von Mises equivalent stress field at the region of the skirt to shell attachment at a specific time point of the preheating phase of the cycle.
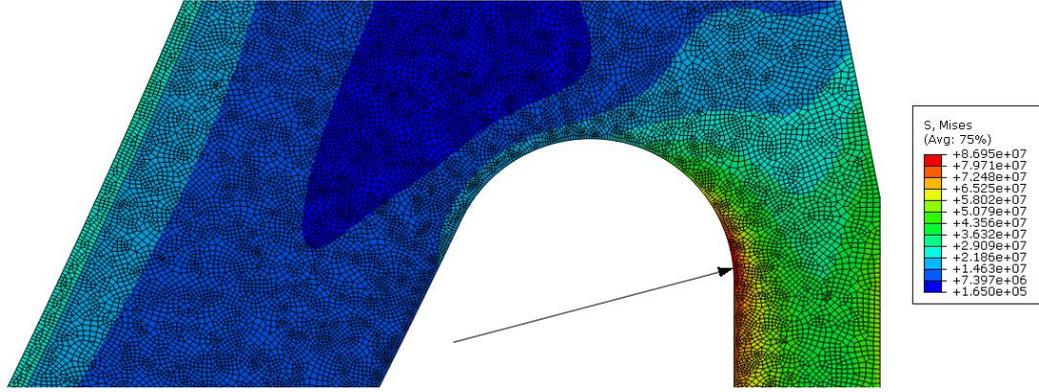
Figure 3. Von Mises equivalent stress field (the arrow indicates the critical point).

4.3 Fatigue life calculation

The fatigue life calculation is done in accordance with ASME Section VIII Division 2 (2007) Part 5. The stress component ranges between time points ^{m}t and ^{n}t are obtained through Eq. (2). The time point ^{m}t is when the lowest valley, in this specific case, of stress occurs and is at the filling stage. The time point ^{n}t is when the highest peak of stress occurs. It forms a range with time point ^{m}t and, in this specific case, is at the cooling stage.

$$^{mn}\Delta\sigma_{ij} = {}^{m}\sigma_{ij} - {}^{n}\sigma_{ij} \,. \tag{2}$$

The model of the present study is plane and axisymmetric, therefore $\Delta\sigma_{13} = \Delta\sigma_{13} = 0$, and the von Mises equivalent stress range is obtained as presented in Eq. (3).

$$\Delta\sigma_{eq} = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11} - \Delta\sigma_{22}\right)^2 + \left(\Delta\sigma_{11} - \Delta\sigma_{33}\right)^2 + \left(\Delta\sigma_{22} - \Delta\sigma_{33}\right)^2 + 6.\Delta\sigma_{12}^2\right]^{0,5} \,. \tag{3}$$

The alternating equivalent stress, is determined by Eq. (4).

$$\sigma_a = \frac{\Delta\sigma_{eq}}{2} \,. \tag{4}$$

Finally, the number of allowable design cycles (N) is obtained through Eq. (5):

$$N = 10^X.(\frac{E_T}{E_{FC}}) \,, \tag{5}$$

where E_T is the modulus of elasticity of the material under evaluation at the average temperature of the cycle, $E_{FC} = 195$ GPa is the modulus of elasticity used to establish the design fatigue curve given by ASME Section VIII Division 2 (2007) Part 5, and X is calculated by Eq. (6).

$$X = \frac{C_1 + C_3(\sigma_a/C_{us}) + C_5(\sigma_a/C_{us})^2 + C_7(\sigma_a/C_{us})^3 + C_9(\sigma_a/C_{us})^4 + C_{11}(\sigma_a/C_{us})^5}{1 + C_2(\sigma_a/C_{us}) + C_4(\sigma_a/C_{us})^2 + C_6(\sigma_a/C_{us})^3 + C_8(\sigma_a/C_{us})^4 + C_{10}(\sigma_a/C_{us})^5} \,. \tag{6}$$

The C_1 to C_{11} coefficients for fatigue curve and C_{us} conversion factor (equal to 6,894757 for stresses in MPa), are given by ASME Section VIII Division 2 (2007) Part 3.

5. RESULTS AND DISCUSSION

A fatigue life (N) of 59,633 cycles is estimated for the coke drum under study, through the procedure described in the previous chapter, considering the actual operating conditions (denominated reference configuration - RC). The parameters of the coke drum fatigue life calculation are presented in Tab. 1.

The stress components and the von Mises equivalent stress curves at the critical point throughout the whole cycle,

whose duration is 43.44 h, are presented in the graphic of Fig. 4.

By modifying some parameters of the finite element model, executing new simulations and recalculating the fatigue life, the modified configurations (MC) are obtained.

Table 1. Parameters of the coke drum fatigue life calculation - RC.

$\Delta\sigma_{11}$ (MPa)	$\Delta\sigma_{22}$ (MPa)	$\Delta\sigma_{33}$ (MPa)	$\Delta\sigma_{12}$ (MPa)	$\Delta\sigma_{eq}$ (MPa)	σ_a (MPa)	$T_{méd}$ (°C)	E_T (GPa)	N (cycles)	Life (years)
-0.927	-271.9	47.0	25.8	301.2	150.6	253.8[1]	189.7	59,351	294

The results obtained in the MC are summarized in Tab. 2 and indicate the influence of these parameters on the fatigue life of the equipment.
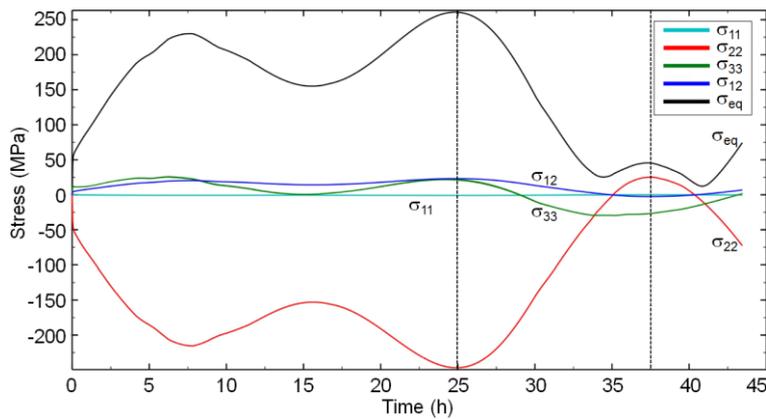

Figure 4. Stresses at the critical point throughout the whole cycle.

In the case where the temperatures in the lower and intermediate regions of the skirt are 20% lower than in the reference configuration over the whole cycle (MC3), the fatigue life reduces 4.6%. The opposite occurs in MC4, in other words, the fatigue life increases 4.1% in the configuration in which the temperatures of the inferior and intermediate regions of the skirt are 20% higher than in RC throughout the whole cycle. When the temperature difference T_{T1} - T_{T0} is reduced by half, in MC5, the fatigue life increases almost 10%. When temperatures throughout the skirt are 20% lower than the RC over the entire cycle in MC6, the number of design cycles reduces 81.3% (N=11,072).

Table 2. Parameters of the coke drum fatigue life calculation - MC.

	RC	MC3	MC4	MC5	MC6	MC7	MC8
$\Delta\sigma_{eq}$ (MPa)	301.2	305.1	298.0	294.0	507.5	318.8	377.8
σ_a (MPa)	150.6	152.5	149.0	147.0	253.8	159.4	188.9
N (cycles)	59,351	56,617	61,796	65,089	11,072	49,097	28,956
N_{MC}/N_{RC} (%)	-	95.4	104.1	109.7	18.7	82.7	48.8
Life (years)	294	281	306	328	54,9	243	147

Although these four modified configurations are theoretical, they show that the temperature gradient in the skirt to shell attachment has a strong effect on the fatigue life of the coke drum based on the critical point located at the upper end of the inner surface of the skirt. The temperature differences between the upper and intermediate regions of the skirt, calculated through Fourier series in these modified configurations except MC6, and in RC are shown in Fig. 5.

The two last evaluated cases take as reference two real cycles in which the switch temperatures (236°C for MC7 and 211°C for MC8) are lower than the average switch temperature of the 5 cycles of the reference configuration (255°C). In these conditions, considering that all cycles have this reduced switch temperature, the estimated fatigue lifes are 17.3% and 51,2% lower, respectively. In MC8 the Fourier series utilize 29 coefficients, more than the 5 coefficients utilized in RC and MC7. The results show a better approximation, or lower values of the error function (Eq. (1)), of the Fourier series to the experimental data when the number of coefficients is higher. The approximation is even better when the optimization process is executed with experimental data from only one cycle, like in MC7 and MC8. Fig. 6 shows the experimental temperatures obtained from thermocouples position T2 and the Fourier series approximation

which is obtained in MC8. Fig. 7 shows a graph of the temperature differences between the shell (T_{T2}) and the skirt (T_{T1}), calculated through Fourier series, in RC, MC6, MC7 and MC8. The evident difference in the aspect of the curves MC7 and MC8 occurs due to the number of coefficients of the Fourier series in each case: 5 and 29, respectively.
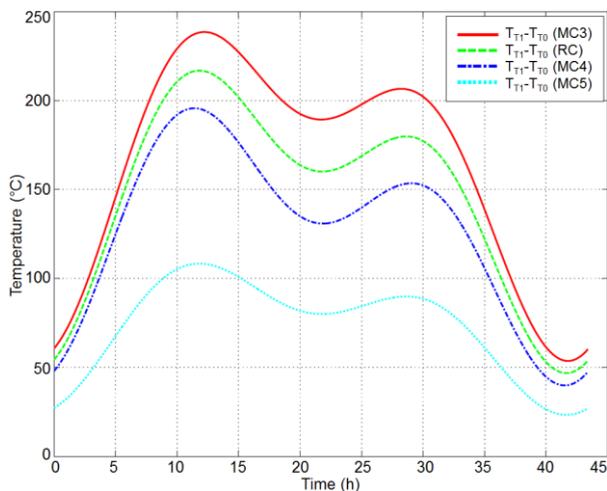

Figure 5. Temperature differences between the upper (T_{T1}) and intermediate (T_{T0}) regions of the skirt, calculated through Fourier series, in RC, MC3, MC4 and MC5.
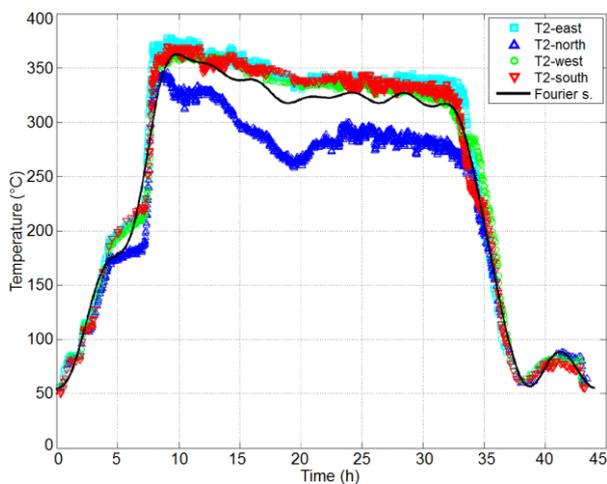
Figure 6. Experimental temperatures from thermocouples in position T2 and Fourier series approximation (MC8).
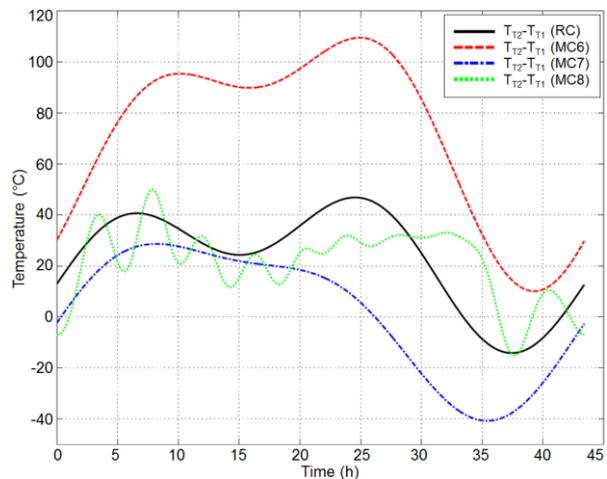

Figure 7. Temperature differences between the coke drum shell (T_{T2}) and the skirt (T_{T1}), calculated through Fourier series, in RC, MC6, MC7 and MC8.

Fig. 8 shows a graph of the stress components and the von Mises equivalent stress curves at the critical point throughout the whole cycle, calculated in MC8. The different aspect of the curves and time points in which the lowest valley and the highest peak of stress component $\Delta\sigma_{22}$ occur can be seen by comparing Fig. 8 with Fig. 4.
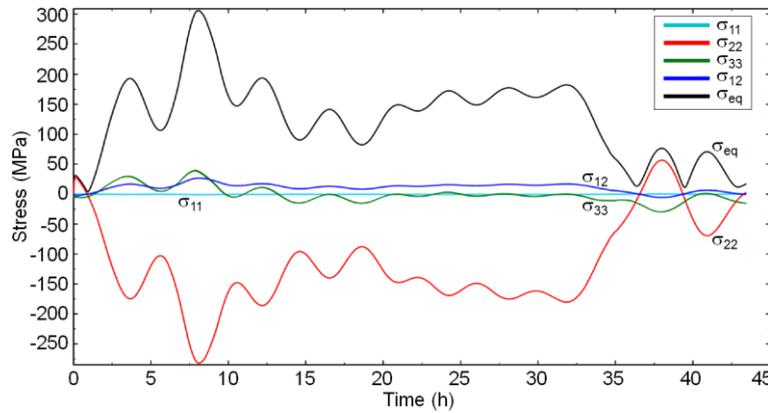

Figure 8. Stresses at the critical point throughout the whole cycle in MC8.

Fig. 9 presents a graph of switch temperature versus fatigue life of the resulting points of the calculation from RC, MC7 and MC8 which shows the linear correlation between these two variables.
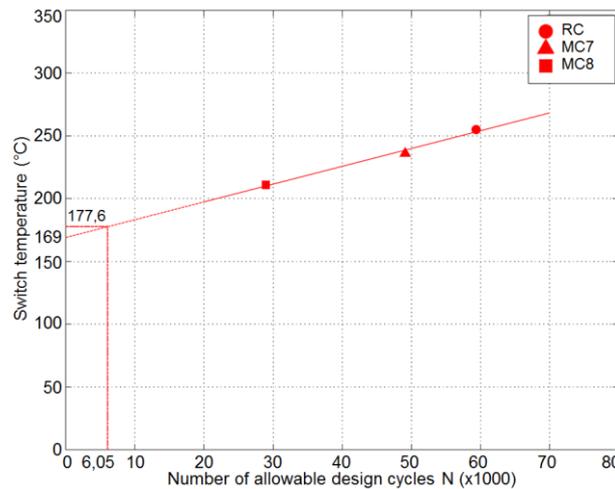

Figure 9. Correlation between fatigue life and switch temperature.

The results evidentiate a strong influence of the temperature field in the skirt on the fatigue life of the coke drum, with respect to the critical point located at the upper end of the inner surface of the skirt. This is an expected result since the skirt temperatures and their relation to the shell temperatures have a direct influence on the thermal stresses in the skirt to shell attachment. The reduction of 50% in the temperature gradient between the upper and intermediate regions of the skirt throughout the entire cycle increases the fatigue life by about 10%. These results reinforce the importance of the hot box project and of the correct instalation of the external thermal insulation in this region.

The switch temperature showed a strong influence on the fatigue life of the equipment: in an approximate and linear form, for each 1°C of change in this temperature, the equipment will have a directly proportional variation of 1% on its fatigue life, in the calculated range.

The RC considers 5 different cycles and is observed a mean switch temperature of 255°C. In this configuration, the fatigue life is much higher than that calculated by the project of the equipment, therefore it can be reasonable the adoption of this value as an operational minimum reference to the coke drum under study.

6. ACKNOWLEDGEMENTS

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