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New Methodology for The Determination of The Failure Times in an Ammonium Carbamate Condenser

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This paper presents a new methodology to determine the optimal maintenance intervention times in the most failure prone components for an ammonium carbamate condenser. The studied condenser takes part of the process of synthesis and high-pressure recovery of synthetic urea, in a plant located in south Mexico, where the substance of the operation promotes important wear effects in industrial equipment. By implementing this methodology, we can calculate the failure times due to material wear for each individual component of de condenser, and consequently schedule specific assessment periods. For this, the minimum material thicknesses required to withstand the operating pressure are calculated according to in the American Society Mechanical Engineers (ASME,2013). The excessive maintenance expenses due to the assessment of the complete industrial equipment, can be reduced by evaluating only the necessary components that integrate the equipment, according to the determined periodicity.

1. Introduction

Synthetic urea (NH_2CONH_2) is a product used mainly as fertilizer, so its production is very important in the petrochemical industry. It is produced by synthesis from NH_3 (ammonia) and CO_2 (carbon dioxide) at high pressure (132 - 305 kg/cm^2) and high temperature (170 – 200 ºC), in this first reaction an intermediate product called ammonium carbamate is formed which in turn gives rise to the second reaction where the ammonium carbamate is dehydrated and partially converted to urea (Hamidipour et al., 2004).
There are several types of synthetic urea production process, such as: partial recycling and total recycling. The most commonly used technologies under the total recycling process are Stamicarbon and Snamprogetti.
The equipments with the highest vulnerability index within the total recycling process patented by Snamprogetti are those that are within the stage of synthesis and recovery at high pressure such as: the reactor, stripper, high pressure decompositor, low pressure decompositor and the carbamate condenser, because the ammonium carbamate is a highly corrosive substance. In turn, such equipments are directly related to production volumes and in case of the existence of faults in any of its components that cause its inoperability would represent a great financial loss.
According to the history of repairs of the equipment, it has been determined that the main cause of the breakdowns is corrosion, this phenomenon causes problems of leakage in the welding joints thanks to maintains a close relationship with the aggressiveness of the substance of operation and the incorrect selection of the construction material used.
In order to assess the condition of the welding, several studies have been carried out such as Javadi et al. (2013) who have implemented the ultrasonic method in the measurement of axial tension, circumferential thickness of an austenitic stainless steel tube, as well as the estimation of residual welding stresses.

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Another relevant study to identify defects in weld joints as well as the physical state of the microstructure of both the tube and the plate of a concentric tube heat exchanger is carried out by Liu et al. (2016) who used metallographic tests and determined by this means serious defects in the welded joint from tube to tube. Ai et al. (2016) proposed an optimization method when taking into consideration the integrity of the weld seams and the welding area for the implementation of fiber laser welding (FLW) in steel with low carbon content and stainless steel. The results obtained indicate that the proposed method is effective to improve the reliability and stability of welded joints in practice.
In fact, these studies contribute in the evaluation of the mechanical condition of industrial equipment and its components; however, it is necessary to determine the periodicity of the inspections of each component that integrate an industrial equipment to avoid excessive expenses for preventive maintenance.
Based on this, the main objective of this work is to estimate the failure times due to material loss of the ammonium carbamate condenser, based on knowing the corrosion rate with which the AISI 316 L stainless steel wears and knowing the minimum thicknesses calculated under the criteria of the American Society Mechanical Engineers (ASME, 2013). It is intended to propose efficient interventions to minimize unscheduled shutdowns of the system, reduce maintenance costs and indirectly maintain production efficiency.

2. Case study

The urea production plant located in south of Mexico was designed under the total recycling process of Snamprogetti. It has a design capacity of 1,500 t/d, the process is divided into the following stages: 1) synthesis and high-pressure recovery section, 2) medium pressure purification and recovery section, 3) low pressure purification and recovery section, 4) vacuum concentration section, 5) prilling section and 6) hydrolysis section.
The carbamate condenser is located inside the synthesis and high-pressure recovery section, its main function is to recover and reuse the CO_2 and NH_3 that did not react coming from the top part of the stripper together with the carbamate without decomposing coming from the bottom of the absorption column, to then separate the liquid phase from the gas in the carbamate separator and be recycled to the reactor (Eni Saipem, 2014).
The condenser analysed is a shell and tube heat exchanger of type horizontal reboiler one-step. The ammonium carbamate is used as stream inside the tubes at an inlet temperature of 180 °C and outlet of 170 °C with a pressure of 150 kg/cm^2, the fluid responsible for absorbing the heat of the operating substance is steam and condensate at a constant temperature of 147 °C and pressure of 5 kg/cm^2. The equipment is constructed with different materials shown in Table 1 components:

Table 1: Construction materials of carbamate condenser.

Components	Shell	Tubes
Flat cover	-	A-150-316L
Hemispherical head	-	A-516-316L
Tubesheet	-	A-150-316L
Coating	-	A-240-316L
Shell	A-516-60	-
Tubes	-	A-213-316L
Nozzle	-	A-516-316L

According to the repairs history of the carbamate condenser, the failures fall on the welding joints of the following components of the equipment: flat cover, hemispherical head, nozzle and tube sheet.
The results of non-destructive tests have shown the presence of undercuts, erosion and cracks in the weld (Figure 1) and there have even been cases of equipment stoppages due to leakage problems due to the loss of material over time. This scenario is associated to the fact that the operating substance is highly corrosive at temperatures in a range of 180 ºC to 250 ºC and pressures around 185 kg/cm^2, in addition to that the change of state accelerates corrosion in the parts in contact with the equipment.
The common faults registered in the exchangers are leaks due to aging and thermal stress. The early and accurate detection of such failures in operation mode is the main task that the fault diagnosis system must achieve (Habbi et al., 2009).
Juneja et al. (2013) mention that the performance of a urea plant is closely related to its construction material since it essentially affects the reliability, operability and maintenance of the same. The corrosive behaviour of the synthesis fluid has forced the urea manufacturing industry and the steel industry to develop new materials capable of withstanding severe production conditions.

Figure 1: Inspection test in mirror top side

Currently the optimum construction materials for this type of aggressive environments are: zirconium, titanium, stainless steel duplex (SAFUREX and DP-28W) and stainless steel (25Cr-22Ni-2Mo and 316L UG). The material 316L UG (grade urea) is an improved version of the alloy 316L, the resulting composition gives the steel a greater resistance to corrosion. In addition, thanks to its good solderability and low cost it is widely used in urea production plants. However, it requires a large amount of passivation air in the high-pressure synthesis and recycling section which restricts its operability.
It is important to recognize that the main cause of breakdowns in the carbamate condenser is the material with which it was built, since in the welding joints in direct contact with the working substance is used the stainless steel AISI 316L. This problem highlights the need to have an accurate and timely maintenance so as not to risk the efficiency of production.

3. Materials and Methods

Based on the above, this situation has led to the development of a new method to estimate failure times through the loss of material from the exchanger and identify the appropriate periods of maintenance interventions. The assessment consists of 3 stages: 1) calculation of the corrosion rate of the material, 2) calculation of minimum thicknesses of design and operation, 3) estimation of failure times and plan of maintenance interventions.
As in any thermal analysis, it is important to define the working fluids and thus the operating and design conditions. For the development of this methodology it is necessary to determine the type of fluid, the interval of temperatures and pressures in the design and operation stages, construction specifications such as: dimensions, thickness and material of the components that make up the equipment, as well as the efforts of tension, efficiency of joints and the corrosion factor.

3.1 Calculation of the corrosion rate

There are several ways to know the corrosion rate of a specific material in function on the temperatures and pressures of the fluid in contact, through direct measurement, consulting historical records of equipment thicknesses or predictive methods. The corrosion rate according to Muñoz et al. (2009), is calculated by means of an equation based on making two measurements made at the same point and in a known time interval, which is explained below:

$$V_C = \frac{E_i - E_f}{T} \tag{1}$$

where:
V_C: Corrosion rate.
E_i: Initial thickness.
E_f: Final thickness.
T: Time elapsed since the last measurement.

However, there are particular cases where the thickness records of the equipment are completely unknown. For this type of situation, the records of corrosion rate indices that are compatible with the construction material and the type of fluid at different temperature and pressure conditions will be consulted. Based on these records, a regression analysis can be performed and find the coefficient of determination R^2 to calculate the goodness of fit of the proposed model.
For this evaluation, the corrosion values reported by De Jonge et al. (1975) are used, since the record of the corrosion rate belongs to equipment of the synthesis and recovery section of a urea plant with approximately the same pressure conditions, these values are only a function of the operating temperature. So, the value of

the corrosion rate according to the average operating temperature of the condenser will be estimated by applying the simple linear regression equation, as shown below:

$$Y = aX + b \tag{2}$$

where:
a: It is the slope of the line which measures the change in the variable Y for each unit of change in the variable
X: It can manifest as that predictor variable.
b: Corresponds to the ordinate to the origin, is the point where the line intersects the Y axis.

It is important to determine the goodness of the fit of the model to decide whether the linear fit is sufficient or to look for other alternative models. So, we must evaluate the coefficient of determination R^2 that corresponds to the square of the correlation coefficient, as shown in Eq(3):

$$R^2 = r^2 \tag{3}$$

$$r = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{4}$$

where:
R^2: Coefficient of determination.
r: Person correlation coefficient.
σ_{xy}: Covariance.
σ_x: Standard deviation in X.
σ_y: Standard deviation in Y.
The values of R^2 must always be between 0 and 1, the closer the result is to 1 means that the goodness of fit of statistical model is better (Verma, 2005). The proportion of 1-R^2 corresponds to the variation that can't be explained within the model, which is attributed to the error in the linear model or events that can't be determined based on any of the variables contained in the regression used.
To determine the reliability of the results obtained, the significance test of the Pearson correlation coefficient was carried out, for this calculation development a test based on the Student's t-distribution (S_r) considering the degrees of freedom as n-2 to 95 % due to the size sample small, as shown in Eq(5):

$$Significance_r = (S_r)(t, gl_{n-2}) \tag{5}$$

$$S_r = \sqrt{\frac{1 - r^2}{n - 2}} \tag{6}$$

where:
Significance: Significance of Person.
S_r: Error of the Pearson coefficient.
r^2: Person coefficient squared.
n-2: Degrees of freedom.

Pita and Pertega (2001) make reference to that if the calculated correlation coefficient (r) exceeds the value of the standard error multiplied by the student's T (n-2 degrees of freedom), it can be determined that the correlation is significantly positive.

3.2 Calculation of minimum thicknesses of design and operation

This phase focuses on the calculation of minimum thicknesses considering the values of the pressure conditions in the design and operation stage under the criteria established in the American Society Mechanical Engineers (ASME, 2013). In function on the geometry of the components to be evaluated, the pertinent equations are exposed for the calculation of each of them:

$$t_{tapa\ plana} = D\sqrt{\left(\frac{CP}{SE} + 1.9\frac{Whg}{SEd^3}\right)} \tag{7}$$

$$\mathrm{t_{semiesférica}} = \frac{\mathrm{PR}}{\mathrm{2SE - 0.2P}} \tag{8}$$

$$t_{cuello} = \frac{PR}{SE - 0.6P} \tag{9}$$

$$t_{espejo} = \frac{FD}{2}\sqrt{\left(\frac{P}{SE}\right)} + C \tag{10}$$

where:
t: Minimum calculated thickness of design (t_d)/operation (t_o).
P: Design pressure (P_d)/operation (P_o).
R: Interior radio.
D: Inside diameter.
S: Design effort to tension.
E: Efficiency of joints.
W: Total load of screws.
hg: Lever arm.
C: Permissible corrosion factor.
F: Factor for fixed mirrors.

In the calculation of minimum design thicknesses (t_d), the pressure calculated in the design stage is taken as a reference. When the operating pressure is greater than 21 kg/cm^2, the design pressure is 1.1 times the operating pressure, as shown in Eq(11):

$$P_d = 1.1\ P_o \tag{11}$$

The evaluation of minimum thicknesses both of design (t_d) and operation (t_o), is done for each of the components.

3.3 Estimation of failure times and plan of maintenance interventions

The evaluation of the time of occurrence of the failure is estimated by plotting three possible scenarios. 1) Time in which the material reaches the maximum allowed corrosion (F_{wc}), 2) Time where the material reaches the minimum design thickness (F_{wd}), 3) Critical time where the material reaches the minimum operating thickness (F_{wo}), that is, F_{wo} represents the worst scenario due to the occurrence of possible leaks in the system. The variables are calculated based on the following expressions:

$$F_{w_c} = \frac{t_c}{V_c} \tag{12}$$

$$F_{w_d} = \frac{t_s - t_d}{V_c} \tag{13}$$

$$F_{w_o} = \frac{t_s - t_o}{V_c} \tag{14}$$

where:
t_c: Maximum allowed corrosion thickness.
t_s: Thickness selected by the manufacturer.
t_d: Minimum design thickness.
t_o: Minimum operation thickness.
V_c: Corrosion rate.
To propose the periodicity of maintenance in an efficient manner, the intervention times of the equipment must be determined between the occurrence of scenario F_{wd} and F_{wo}. On this period the thickness of the material is adequate to resists the operating pressure. If the execution of maintenance is not respected in the established period, possible cases of leakage in the system may start to occur.

4. Analysis of results

The speed with which corrosion advances through time in the AISI 316L material is 17.75 mm/y, this value has been calculated with an average operating temperature corresponding to 175 ºC, performing a simple linear regression. The goodness of fit of the model gives 0.8911 as a result, which means that 89.11 % of the total variability is explained in the model used. The reliability of these data based on the result of the significance test of the Pearson correlation coefficient reveals a 95 % safety, considering n-2 degrees of freedom.
The results presented below correspond to the evaluation of the components with recurrence to the failure. In Table 2, the calculated thicknesses and the possible times of occurrence of each scenario are shown.

Table 2: Analysis of failure times of the carbamate condenser

Components	Thicknesses			Failure Times		
	t_c (mm)	t_s (mm)	t_d (mm)	F_{wc} (d)	F_{wd} (d)	F_{wo} (d)
Flat cover	3.20	210	146.60	65	1,303	1,325
Hemispherical head	3.20	60	50.74	65	190	286
Nozzle	3.20	136	36.44	65	2,047	2,120
Tubesheet	3.20	305	290.50	65	298	572

Based on the times of occurrence of each scenario, the implementation of non-destructive inspection tests (PND's) is suggested, in order to evaluate the condition of the components and perform the corresponding repairs in the following periods:

1. Hemispherical head: Every six months.
2. Tubesheet: Every year.
3. Flat cover: Every three years.
4. Nozzle: Every five years and six months.

As part of the implementation of this methodology, favorable results were obtained. Following with the maintenance plan of the ammonium carbamate condenser this equipment went out of operation every 6 months so that the operators would evaluate each one of its components. Now, thanks to this proposal, the costs of preventive maintenance and equipment downtime have been reduced. On a first stage, for components such as the Tubesheet and the Flat cover, what previously represented 100 % maintenance cost, it was reduced to 75 % and 35 % respectively.

5. Conclusions

The estimation of the failure times of an industrial equipment can be determined in various ways and based on various variables. In this work, we presented an alternative method, for the case of a condenser, which allows not only to predict the failure times, but also to know the condition of the material thicknesses of its various elements, without the use of any measuring tools. The proper implementation of this method could avoid excessive costs for maintenance intervention, ensure the safety of operators responsible for operation and indirectly reduce the loss of production due to unplanned maintenance.

Based on the criteria used in this methodology, a maintenance proposal was made, in which the number of interventions for the different components of the condenser was significantly reduced. It is also expected to apply them in the evaluation of any type of pressure vessel, such as: reactors, columns, heat exchangers, storage tanks, etc., adapting the conditions for each case and even based on this reasoning.

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