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Failure detection in a pressure vessel using acoustic emissions technology

Detección de fallas en un recipiente sometido a presión usando la tecnología de emisiones acústicas

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Abstract

The acoustic emission (AE) technique was implemented to monitor different failure stages in steel cylinders used to store Liquefied Petroleum Gas (LPG). Experiments in two containers with external and internal defects subjected to a hydrostatic test were carried out. The severity of the faults was progressively increasing through the different stages to study the microseismic activity. The experimental tests allowed checking the Kaiser and Felicity effects. Additionally, it was observed that an increase in the severity of the failure depicts an increase in the number of hits, counts and energy values detected. The evolution of the acoustic activity for the different failure stages established the container's structural integrity, proving that AE allows evaluating its entire condition.

Keywords: LPG cylinders; AE damage detection; acoustics emissions; microseismic activity; pressure container.

Resumen

En este artículo se implementó la técnica de emisiones acústicas (EA) para monitorear diferentes escenarios de falla en cilindros de acero usados para almacenar gas licuado del petróleo (GLP). Los experimentos se llevaron a cabo en dos recipientes con defectos externos e internos sometidos a una prueba hidrostática. La severidad de las fallas fue aumentando progresivamente a través de los distintos escenarios con el fin de estudiar la actividad microsísmica. Las pruebas experimentales permitieron comprobar los efectos Káiser - Felicity y se observó que un aumento en la severidad de la falla representaba un incremento en la cantidad de hits detectados, cuentas y valores de energía. La evolución de la actividad acústica para los diferentes escenarios de falla determinó la integridad estructural de los contenedores, demostrándose que las EA permiten evaluar la condición global de los cilindros.

Palabras clave: GLP; actividad microsísmica; emisión acústica; integridad estructural; recipientes a presión.

1. Introduction

The evaluation of the structural condition of pressure vessels is carried out through Non-Destructive Testing (NDT) [1]. Nevertheless, tests such as ultrasound, industrial radiography and electromagnetic particles, among others, are active methods that require the external application of energy to assess the material condition.

Unlike the aforementioned methods, acoustic emission (AE) is a passive one, in which discontinuities in the material release energy as the structural components are subjected to load or stress. Then, the energy released

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travels through the material as sound waves that spread cylindrically, and a transducer receives and converts it to a voltage signal for it to be processed as data of acoustic or microseismic activity [2].

Considering the above, the technique of acoustic emissions offers both economic benefits and advantages from the point of view of maintenance or structural condition evaluation due to the global nature of the test, detecting imperfections in any place in the volume examined and facilitating the conduct of in-service inspections. However, the location of a failure cannot be determined without having a specific number of microseismic activity sensors [3].

Some implementations of the AE technique are the detection of fatigue crack or corrosion and the detection of imperfections in the weld and casting [3], [4], [5]. Also, multiple pieces of research have been conducted for the monitoring of pressure vessels in every field of the industry, achieving the evaluation of the structural integrity of the cylinders made of steel, composite materials [6], [7], [8] and gas storage spheres essential in refineries [9]. In the present paper, the AE technique is implemented during a hydrostatic pressure test with the aim of monitoring the acoustic activity of two LPG cylinders when increasing the severity of the fault imposed in the posed staged.

2. Theoretical analysis

AEs are a non-destructive method of inspection employed in the industry that seeks to detect, locate and evaluate discontinuities in materials. It is based on the study of waves produced by rapid energy release of material discontinuities when said material is under mechanical stress. In other words, they manifest in locations where the punctual stress is strong enough to cause permanent deformations

When a material is deformed due to a punctual stress, this action tends to alleviate the stress located, and the load tends to transfer to somewhere else in the structure in the form of acoustic activity. This causes a stabilizing effect. Nonetheless, if the structure frees itself from the load and then, is loaded again at the same previous level, the regions that were deformed in the first place are more likely to be more stable the second time. This phenomenon is called Kaiser effect.

Furthermore, a phenomenon appears when the acoustic activity is obtained before it reaches the maximum level of load, with which the material was stimulated in the previous procedure [10]. The phenomenon is known as Felicity effect.

2.1. Parameters of an AE signal

The data contained in the acoustic signal is expressed through certain characteristics; some are related to the detection threshold as shown in Figure 1. The parameters are the following:

- Threshold: is minimum voltage level established to reset the detection of an AE signal.
- Amplitude: refers to the greatest voltage present in the waveform of a signal and is expressed in decibels (dB).
- Duration: is the time difference between the first threshold crossing and last threshold crossing.
- Rise time: is the time interval between the first threshold crossing and the moment the signal peak (amplitude) is reached.
- Counts: refers to the number of pulses greater than the established threshold.
- Energy: concerns the area under the envelope of the rectified linear voltage time signal from the transducer. This is a relevant measure of signal size, and it is used the most for the measurement of AE [11][12].

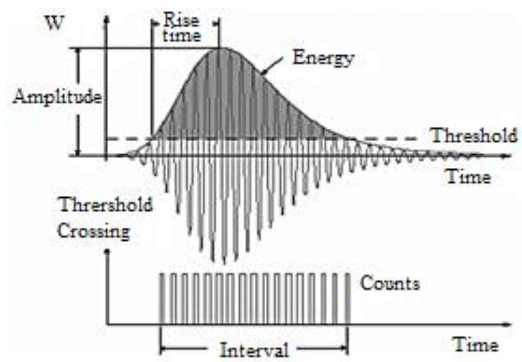


Figure 1. Parameters of an AE signal. Retrieved from http://anonymousmonetarist. blogspot.com.co/2010_03_01_archive.html (2017).

2.2. Evaluation criteria

- Insignificant faults have a tendency to exhibit the Kaiser effect, whereas significant structural failures incline to display the Felicity effect [2].
- As the test is conducted, greater amplitudes are related to more severe deformation mechanisms [10].
- Activity during the hold periods indicates the decline of continuous stresses.
- High amplitude signals demonstrate the presence of failures in growth.
- The increase of accumulated energy reveals the areas of failure corresponding to the increment of load [13].
- Severe failures are identified due to the disproportionate rise in AE activity under loading

(number of emissions and accumulated energy) [10][1][2].
- The increase in the parameters for AE (amplitude, energy) after the increase in loading hints at a structural failure [1].

3. Methodology

In this study, two steel cylinders for commercial uses for the transportation and the consumption of Liquefied Petroleum Gas (LPG) were employed. To simulate various failure stages, the containers were called vessel 1 and vessel 2. Regarding the first, failures are induced on the external surface. In relation to the second, they were caused on the internal surface of its base. The damages made in the cylinders resemble V-shaped circumferential notches [14]. The characteristics of the cylinder to be studied using EA are shown in Table 1.

Table 1. Technical specifications of the LPG cylinder.

Thickness of the wall[mm]	3
Volumetric capacity[L]	18.2
Maximum service pressure [psi]	240
Maximum hydrostatic test pressure [psi]	500
Minimum burst pressure [psi]	960

Own elaboration.

Five failure stages are applied to vessel 1 (see Table 2). In stages 1 and 2, no kind of damage is executed, for it is necessary to be aware of the activity carried out by the container in its original state and prove the Kaiser effect. In stage 3, the mild severity level, notches are made with a depth of approximately 0.5 mm. Afterward, in the stage with a medium severity level, the thickness of the walls are reduced by removing the failures caused in the level with mild severity. Then, new notches are created with an approximate depth of 0.5 mm. Finally, for the high severity level, the thickness is also decreased until the notches in the previous stage are deleted. The procedure was developed considering the ASTM E569 standard[15].

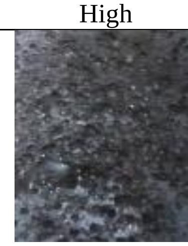
For vessel 2 stages (shown in Table 3), the damages were inflicted in the internal base of the cylinder when a bar with a weight of approximately 0.5 Kg was dropped. The bar was holding a punch at one of its ends, so it created a circumferential notch when it fell. Just as in stages 1 and 2, in stages 6 and 7, it is intended to know the initial behavior of the vessel. In stage 8, 200 notches are made by dropping the bar through the inlet of the vessel at a 0.2m height; this causes a damage of 0.5mm depth, approximately. In stage 9, medium severity, 1000 1mm-deep notches are done by letting the bar fall at a 0.4m height. Lastly, the high severity stage is obtained when dropping the bar 23000 times to the base of the cylinder at a 0.6m height, approximately.

Table 2. Stages of failure for vessel 1.

Vessel 1				
Null	Null	Mild	Medium	High
				

Own elaboration.

Table 3. Stages of failure for vessel 2.

Vessel 2				
Null	Null	Mild	Medium	High
				

Own elaboration.

In the elaboration of the tests, a system dedicated to acoustic emissions capture (EA Node System) of PAC (Physical Acoustics Corporation) is used for the management of AE signals; the software AEwin Lite® is used for the graphic presentation of the data as well. Also, the signal of pressure with a PT124B-210 of the manufacturer ZHYQ [16] [17]. The scheme of the array of the global systems for inspection of vessel 1 and external failures is illustrated in Figure 2. In vessel 2, internal failures will be studied by placing the sensor at the base of the tank.

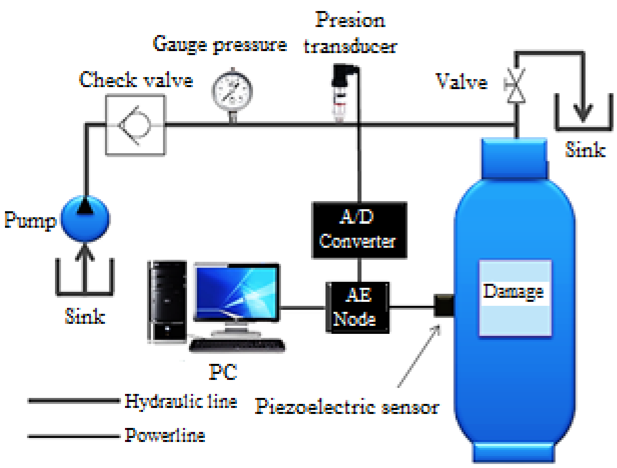


Figure 2. Schematic drawing of vessel.
Own elaboration.

The configuration parameters of the data acquisition system are adjusted in accordance with Table 4, shown below:

Table 4. Configuration of the acquisition channels.

Fixed threshold [dB]	Analogue filter Low High [KHz]	Waveform		
		Sampling frequency [MSPS]	Pre-trigger [µs]	Hit length [KS]
40	20-1000	10	960	7

Own elaboration.

Based on the standards of the ASTM E976-10, ASTM E2374-10 [18] [19], the verification of the performance prior the inspection of the cylinders is done as part of the process; this validates the proper functioning of the equipment and guarantees a high-quality data gathering. Table 5 reveals just the data collected during the first stage.

Table presents the values of the common parameters of an acoustic emission, product of pencil lead breaking. This procedure was implemented in each stage; similarities were found between the values produced by the detected hits, presenting variations of less than 6dB, what is associated to the sensor proper functioning as indicated in section 6 of the regulation ASTM E976-10 [18]. Nevertheless, Table 5 reveals just the data collected during the first stage.

Table 5. Verification of the performance of the AE node for stage 1. stage 1. Own elaboration.

Breaking	Energy µV-s/ count	Amplitude dB	Duration µs	Counts
1	3195	86	35633	1138
2	3513	85	35678	935
3	2244	86	33093	961
4	2624	90	30825	894
5	2990	87	32051	903
6	2909	86	33456	966

To eliminate the noise attributed to the use of electronic transducers, a threshold of >40 dB was provided, based on the amplitudes evidenced in different AE sources [20], [21]. Under said threshold, during the background noise determination period, a waveform with patterns that repeat constantly and also, low amplitude, energy and duration, different from the transient pulses characteristic of an AE, were noticed [12]. Figure 3 and Figure 4 display the difference between the waveform distinctive of noise and the one of an AEs. The AE signal waveform, Figure 4, distinguishes itself because it reaches rapidly the peak amplitude with a decline accelerated after crossing that point [22].

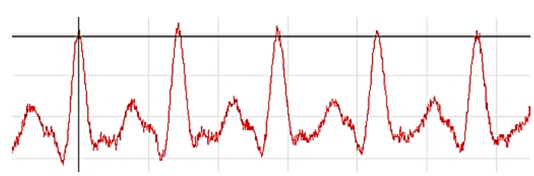


Figure 3. Waveform of the noise signal under the threshold. Own elaboration.

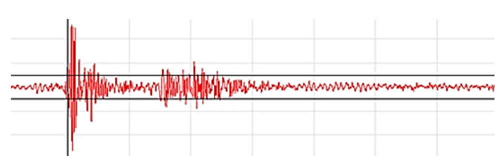


Figure 4. Waveform of a real AE signal.
Own elaboration.

The structural load to which both vessels are subjected is created following the sequence of the pressurization indicated by the standard ASME in section T-1244.3.2.2 [1]. Table 6 reports the values of the hold periods after increasing pressure at a rate of 26.4 psi/min. Figure 5 depicts the pressurization sequence for each failure stage.

Table 6. Pressurization stages for vessel 1 and 2.

Hold period	Failure stages				
	1-6	2-7	3-8	4-9	5-10
N°1 [psi]	432	475	523	575	633
N°2 [psi]	460	528	581	639	703
N°3 [psi]	504	554	610	671	738
N°4 [psi]	528	581	639	703	773

Own elaboration.

4. Results

The results of tests for each proposed stage are summarized in Figures 6-11. In Figure 6, the AE energy recorded in all five failure stages for vessel 1 is analyzed. The pressure values in psi are determined on the left-hand vertical axis for a specific time that is indicated on the horizontal axis. The points refer to a hit or an AE clustering with an energy level specific of the magnitude expressed on the right-hand vertical axis.

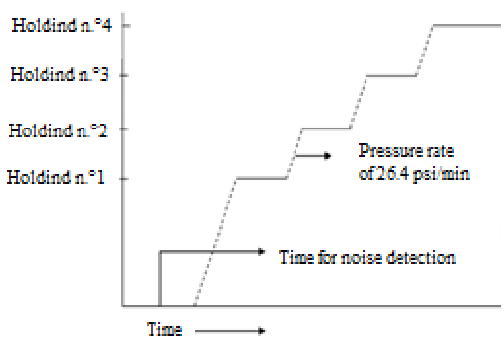


Figure 5. Pressurization sequence for each failure stage. Adapted from [1].

The first comparison is made with stages 1 and 2, which correspond to the conditions of null failures or nominal under the tested vessel. Stage 2 reaches a pressure level 10% greater than the pressure in stage 1, and from there, the first observations about the Kaiser effect in these stages starts [2] [23]; it is like this that the few hits detected in the second test are made when 575 psi is reached, exceeding the previous maximum pressure that was 526 psi. Furthermore, it is noted that when inflicting minor failures (stage 3), changes in acoustic activity are discovered in stage 2. Moreover, the majority of hits distinguished in staged 3 are made in hold periods, which implies the beginning of the material degradation process [23]. At this point, the Kaiser effect can be still recognized, as the first hits in stage 3 detect a pressure level of 632 psi, which overcomes the previous maximum pressure level of 575psi; this is associated to insignificant failures [2][23].

It is important to analyze the Felicity effect experienced in stage 4. In here, the damage is categorized as intermediate, and it is noted the presence of AE energy before reaching the maximum pressure level of the previous stage, with which it can be concluded that failures inflicted affect significantly the vessel integrity. In addition, in this stage of testing, hits of greater energy compared to prior stages can be encountered, relating this with the structural gravity mentioned before. Now, stage 5, that correlates to the maximum severity studied, shows activity since the start of the pressurization, relating this again to the Felicity effect with a greater density of hits compared to stages 2,3 and 4, the product of a higher simulated severity. In Figure 6, the sequence of increment in pressure in the cylinder tested stops abruptly because of the cylinder crack around the affected area. This outcome demonstrates how strongly the vessel integrity was affected during the last stage, that caused the crack at a value of 341 psi far below the minimum value of crack in nominal condition of 960 psi. Thus, a lower acoustic energy value in stage 5 in comparison to the one in stage 1, for both pressure levels, is observed.

Besides, the behavior displayed by the accumulative curves of hits and energy are analyzed in Figure 7. These curves represent the history of vessel 1 AE activity since Acoustic Emission Testing (AET) is first performed (Stage 1) until the failure of the same was achieved (Stage 5). As first observation, there is the fact that although the accumulation of energy until stage 3 (26057 µV-s/ counts) is significant to the global (74672 µV-s/ counts), it presents a moderate increase with negative concavity, proving that the caused failures in the vessel to that moment were not severe [11]. Then, the pronounced growth of the curves in stages 4 and 5 announces the existence of severe failures in the cylinder because first, the greatest part of the accumulative energy is achieved and second, as shown accumulative hits curve for stage 5, a point of inflection is presented in which the curve adopts a positive concavity, alerting the destruction of the cylinder [1] [11].

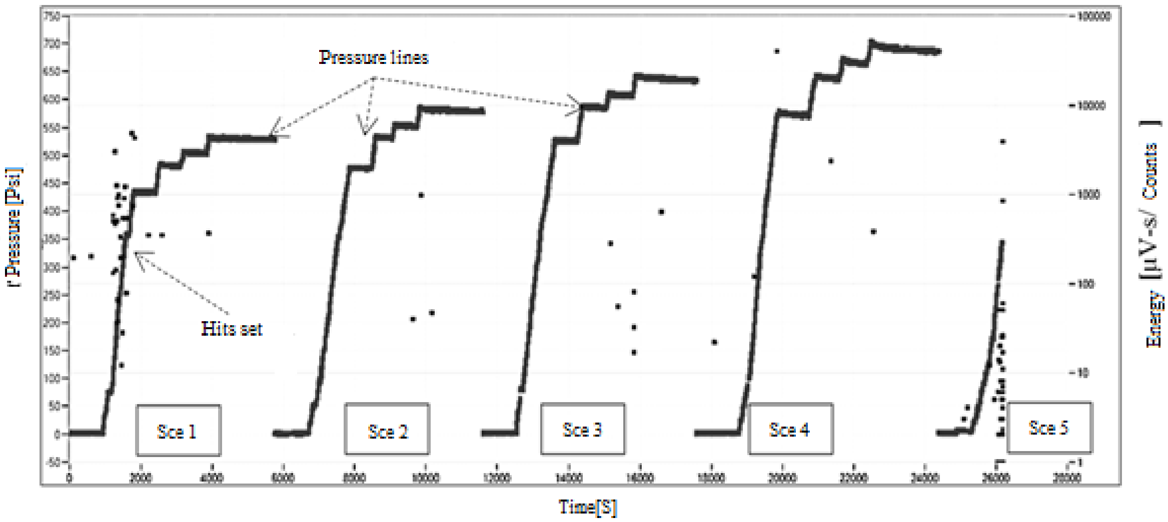


Figure 6. Energy in all failure stages of vessel 1. Own elaboration.

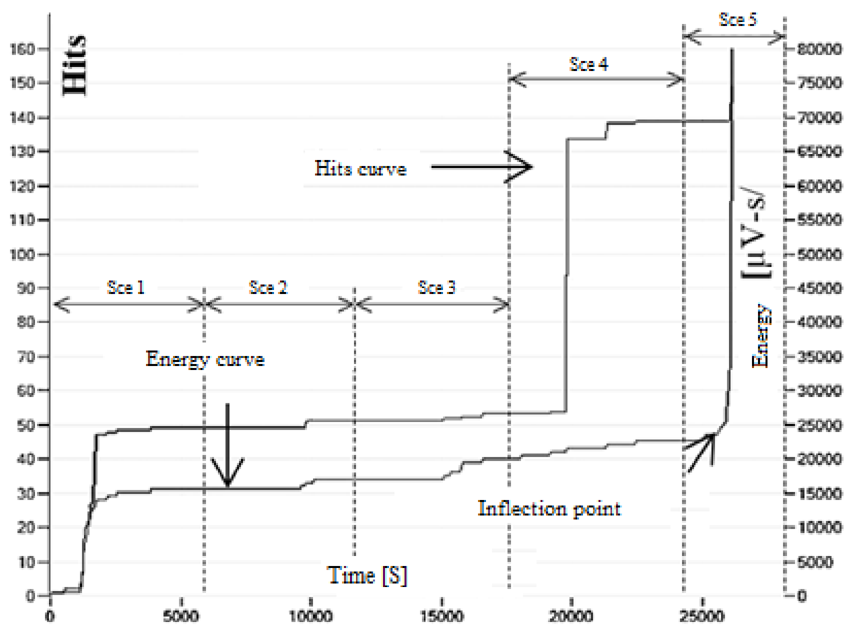


Figure 7. History of acoustic activity of vessel 1. Own elaboration.

Finally, in Figure 8, the accumulative values for energy, hits and counts for each stage of vessel 1. The energy, that associates the number of hits, their amplitude and counts, is a parameter used to measure the acoustic activity. Regarding such parameter, an accumulated energy decrease between stages 1 and 2 from 24532µV-s/count, to 1059µV-s/count can be seen, respectively. Also, stages 1 and 2 are characterized by the fact that no type of damage was caused in the material. type of damage in the material; for this reason, the energy decrease is related to the Kaiser effect. As stated in the previous analysis, when no failures are inflicted in the material (stage 2), the AE activity tends to diminish just as the number of hits and counts detected do as well.

That said, the minor faults are detected since in stage 1 and 2, there a positive change, increasing in energy terms from 1059 µV-s/count to 1096 µV-s/count. The number of hits and counts do it likewise. The rise in the fault severity in the tested cylinder 1 in stages 3 and 4 is noticeable due to the boost of the energy value, going from 1090 µV-s/count to 42678 µV-s/count. It is also relevant to point out that even though the amount of hits accumulated for stage 3 lowered (5 hits) in respect to stage 3 (6 hits), the captured counts escalated quickly from 9544 counts in stage 3 to 20548 counts in stage 4. As described before, this behavior influences the high-value energy in stage 4. Lastly, stage 5 did not increase in terms of AE energy in relation to stage 4, but the number of hits did increase. In short, as energy is associated with the amount of hits and counts, it is the parameter which was granted of the rise of failure severity in stages 2,3 and 4. However, the great acceleration with which hits are produced is the one that characterizes the vessel failure.

Figure 9 illustrates comparatively the acoustic behavior in the different failure stages of vessel 2. The first observation presents the Kaiser effect in stages 6 and 7 since in this last test, most of the hits detected appear in a pressure level (534 psi) higher than the maximum pressure level in the sixth stage (531 psi). Similarly, it is seen among these tests a decrease in AE activity, for the hits detected in stage 7 are lower in number and in energy than those obtained in the sixth one. Thereafter, a change between the eighth and seventh stages is identified; the acoustic activity of stage 8 started during the first stage of pressurization, resulting in the Felicity effect, a phenomenon opposite to Kaiser effect, and the hits identified showed more energy, proving that in this stage, the tank was affected due to the minor faults. Stage 9 displays, in comparison with stage 8, greater energy hits; this confirms that, the damages inflicted are indeed significant; moreover, the Felicity effect is distinguished as there is hits detection in the first phase of pressurization prior to reaching the maximum pressure level in stage 8.

Eventually, stage 10 exhibits the greatest acoustic activity of all tests of the vessel being researched. This test is characterized by causing leaks at the base of the cylinder, finding hits with higher energy each time (when increasing pressure) coming from the spread of cracks in the affected area.

Figure 8. Energy, Hits and Counts accumulated in each stage of vessel 1. Own elaboration.

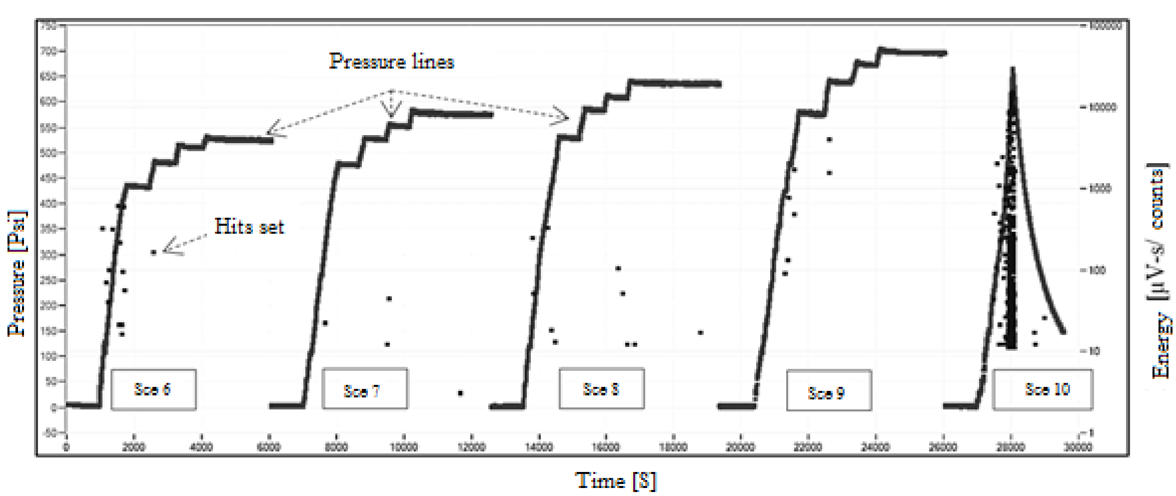


Figure 9. Energy activity in all failure stages of vessel 2 against time. Own elaboration.

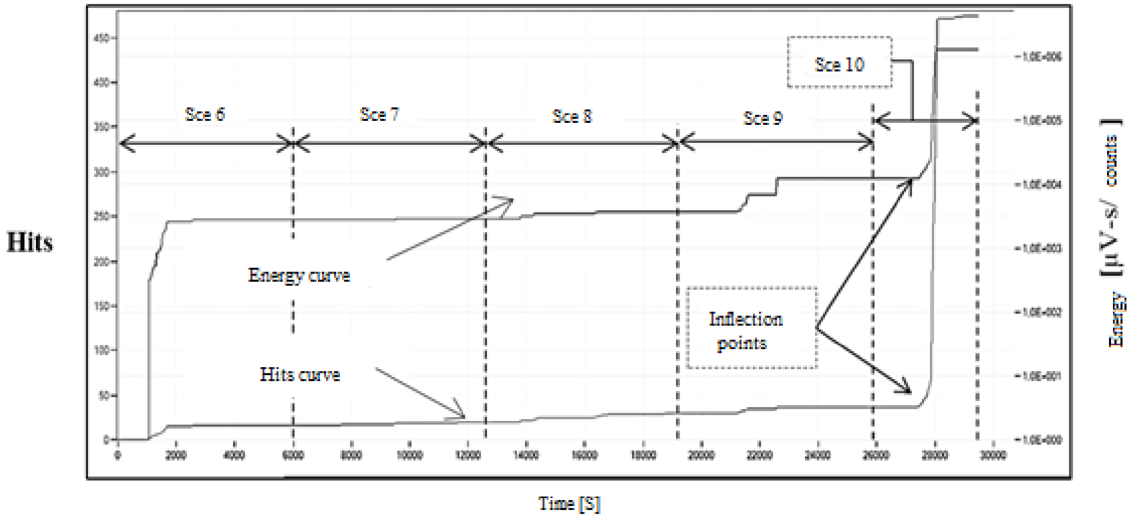


Figure 10. Acoustic activity history cylinder 2. Own elaboration.

In Figure 10, the history of acoustic activity in vessel 2 is reported and allows determining the development of the material degradation. The measured growth that the curves accumulative of hits and energy suffer in stage 6,7 8 and 9 is noticeable, and it entails that until that last test the vessel material has not been notably affected [11]. Furthermore, stage 10 presents for both curves an inflection point, accelerating the clustering of hits and their respective energy during the first minutes of the test, disclosing the material collapse due to a leak. Nonetheless, in this last stage, segments of null gradient are recognized at the end of both curves; this evident change happens when the first pressure level is reached (662 psi), the moment when the pressurization stops, and due to the leak originated, the decrease of pressure in the vessel begins. Therefore, as there is no crack propagation, significant acoustic activity is not produced.

Lastly, Figure 11 allows analyzing the acoustic activity in each stage in vessel 2 and examining the tendencies of accumulated hits growth, the counts and energy values for every stage studied. In general, it is clear when there is a failure and the cylinder is pressed, the acoustic activity is going to lower again as experienced in stages 6 and 7. On the other hand, the infliction of faults each time more severe tends to raise the values of the distinctive parameters of AEs, in global terms, the energy, as it happened in vessel 1.

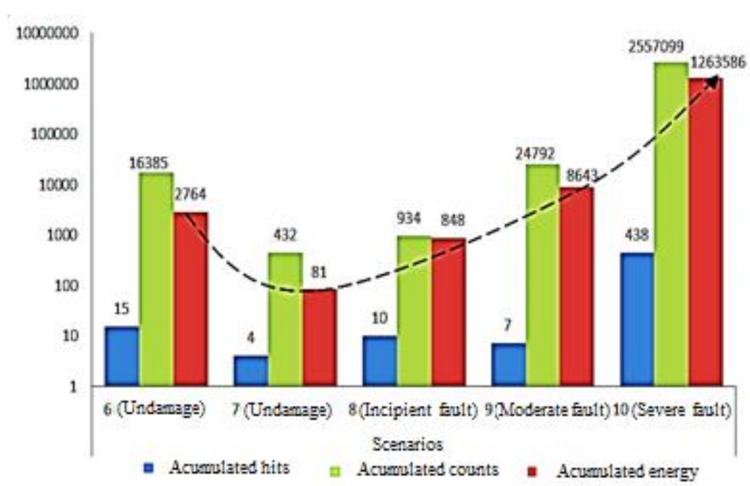


Figure 11. Energy, Hits y Counts accumulated in each stage for vessel 2. Own elaboration.

5. Conclusion

This research studied the acoustic behavior of steel cylinders subjected to external and internal damages employing the acoustic emissions technique. This method enables detecting structural changes that stimulated failure conditions in the vessels being examined.

The phenomenon associated with Kaiser effect was experienced during the data gathering in stage 2 for vessel 1 and stage 7 for vessel 2. For these stages, acoustic emissions were detected in pressure levels higher than the maximum value used in the previous failure stages 1 and 6.

It was addressed that for stages with new failures 3,4 and 5 of vessel 1 and stages 8,9 and 10 for vessel 2, Felicity effect would take place because the microseismic activity would be detected before it reached the maximum pressure level in the preceding stage.

A pressure value higher than the last pressure level applied increases the acoustic activity as in stages 1 and 2 for vessel 1 and stages 6 and 7 for vessel 2. This phenomenon can be interpreted as a false positive of acoustic activity or evidence of failure. Nevertheless, the behavior mentioned can be Kaiser effect.

An increase in the failure severity in the tested vessels unfolded an increment un acoustic activity. Hence, it is possible to monitor the integrity if an LPG container using the history of acoustic activity, with what is possible to predict structural changes or failure presence.

The acoustic activity evolution determined the structural integrity of the vessels, as much as for the cylinder with external damages caused by the reduction of material and the creation of notches as it did for the one with internal damages provoked by the notches during the varying failure stages.

In this work, it was not possible to locate a failure. However, if sensor web is established, it is likely that the data collected by the different nodes predicts the approximate location of the discontinuity, what becomes an advantage that allows acting promptly and accurately about the applicating case in the industry.

Acknowledgments

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