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Detection of Faults in Combustion Engines Through Indicators of Temperature and Injection Pressure

Detección de fallas en motores de combustión mediante indicadores de temperatura y presión de inyección

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Resumen

The present work aims at proposing indicators for early detection of faults in the fuel-oil generator sets of internal combustion engines, using the injection pressure and temperature of the combustion chamber. As a case study, the generation groups of the Maintenance Company of Fuel-Oil Generating Sets (EMGEF), in the Cuban province of Granma, were evaluated. A multifactorial design was used for the experiment, using 16 engines as main factors, the 9 cylinders of each engine, and a working time of 3 years. The study demonstrated that pressure and temperature are significant indicators of engine failure, and that the number of detected faults from temperature were more significant than those reported from injection pressure. It is concluded that high temperatures in the cylinders are generally related to a high index of gases, and a poor state of the injectors. The differences between the pressures are related to low hermetism, and the technical state of the elements of the feeding system.

Keywords: failure, pressure, injection, temperature combustion chamber, maintenance, generator sets.

Abstract

El presente trabajo tiene como objetivo proponer indicadores para la detección temprana de fallas en los motores combustión interna de los grupos electrógenos de fueloil a partir de la presión de inyección y temperatura de la cámara de combustión. Como caso de estudio fueron evaluados los grupos de generación de la Empresa de Mantenimiento a los Grupos Electrógenos Fueloil (EMGEF) en la provincia cubana de Granma. Para el experimento se utilizó un diseño multifactorial usando como factores principales los 16 motores, los 9 cilindros de cada motor y un tiempo de trabajo de 3 años. El estudio demostró que la presión y la temperatura son indicadores significativos en las fallas de los motores, además de que el número de fallas detectadas por temperatura fueron más significativas que las reportadas por la presión de inyección. Se concluye que las altas temperaturas en los cilindros generalmente están relacionadas con un alto índice de gases y un deficiente estado de los inyectores. Las diferencias entre las presiones están relacionadas con la baja hermeticidad y el estado técnico de los elementos del sistema de alimentación.

Palabras clave: fallas, presión, inyección, temperatura, cámara de combustión, mantenimiento, grupos electrógenos.

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1. Introduction

Electricity generation is a priority for governments, because the quality of life of the people largely depends on it. An alternative to guarantee such objective are the generating groups (GG), which are employed either in an intensive manner or as support. They are continuously improved to guarantee their efficiency and effectiveness [1].

As all equipment for distributed generation, the GG have various advantages and disadvantages in their operation, due to the parameters of the manufacturer and of the generators that constitute them. Their main advantages are that they help with environmental conservation, and that they constitute an important alternative to increase electric generation at peak hours of demand, contributing to decongest energy transmission systems. The main disadvantage of this system, is that they can produce voltage fluctuations that may affect nearby generating groups. Besides, it requires a data acquisition system which is more complex, compared to any other equipment, due to technology used in these cases [2, 3].

Several research works have been carried out, to propose techniques for early detection and diagnose of failures in internal combustion engines. According to Mendonça [4], incipient malfunctions in the components of generators driven by internal combustion engines, may be detected measuring the voltage and current in the stator of the generator; such malfunctions may include failures in the inlet valve, and in the compression due to wear in the piston rings. The study carried out by Xi, Li, Tian and Duan [5] showed that it is possible to detect failures in marine combustion engines, from the analysis of the frequency of the vibrations.

On the other hand, the study by Lee, Cha, Ko, Park and Jung [6] deals with fault detection applications and diagnose algorithms based on the Kalman filter and the fault factor method, which are utilized on an open-cycle liquid propellant rocket engine at steady state, enabling to determine the fault location, either in a sensor or in an internal component. In the study carried out by Czech, Wojnar, Burdzik, Konieczny and Warczek [7], vibration signals and artificial neural networks were used to detect damage on the engine mechanical elements (exhaust valves, injectors, cylinder head gasket). The results confirmed the possibility of diagnosing the technical state of the automobile engine components, while the motor is in operation.

Flett and Bone [8] developed a system based in the vibration, for detection and diagnosis of failures in the valve train of the internal combustion engine. On the other hand, Trujillo *et al.* [9] proposed a methodology that combines numerical and experimental procedures by means of finite element simulations, use of thermocouples and infrared thermography, to estimate the mean temperature in the internal surface of the cylinder of an air-cooled direct injection diesel four strokes engine, improving data acquisition and preventing to take actions from the inside of the combustion chamber, thus reducing the complexity of the experiments during diagnosis.

During normal operation, the GG are subject to different requests that cause their deterioration, and consequently reduces their electric generation capacity. This deterioration comprises all forms of wear and tear produced by phenomena such as: fatigue, corrosion, abrasion, erosion and degradation. These failures may be possibly caused by the effect of the injection pressure and temperature accumulated inside each engine cylinder. Therefore, the objective of this research is to propose indicators that use injection pressure and temperature in the combustion chamber, for early detection of faults of fuel-oil generating groups in internal combustion engines.

2. Materials and methods

The Corporate Base Unit of 110 kV, which belongs to the Granma Cuban Electrical Company, is taken as a case study. Such unit is constituted by sixteen generating groups that operate with fuel-oil.

2.1. Extent of the research

The research lasted a period of 36 months (from January 2015 to December 2017). Data and valuable information was obtained from the following documents: i) letter of technological regime for HHI 1.7 MW PPS (Code: UJ-IG-0304); ii) control of availability GDECU (Code: UJ-IG 0105); iii) book of defect control (Code: UJ-MP 0200.A5); iv) book of operational incidences (Code: UJ-MG 0200.A8); v) operating control of faults. Direct queries were carried out to operators and specialists in charge of the GG exploitation, to extract distinctive features of the operation of such equipment.

2.2. Generating groups (GG) main title

The GGs of the station comprise 16 1.7 MW Hyundai engines. Table 1 summarizes the characteristics of such engines. These machines use fuel-oil, which is a fraction of the oil obtained as residue after distillation. Is the heaviest fuel than can be distilled at atmospheric pressure. It is used as fuel in electric generation plants, boilers and furnaces.

Table 1. Characteristics of the 1.7 MW HYUNDAI engines

Type of engine	**HYUNDAY 1,7 MW**
Number of cylinders	9
Rotational speed (min^{-1})	1000
Diameter of the cylinders (mm)	210
Power per cylinders (kW)	200
Piston travel (mm)	320

2.3. Control, analysis and failure criteria

This sub-section specifies the considerations assumed during the experimentation.

2.3.1. Control

All the information regarding failures was collected from the operational record of failures. The following was taken into account in such register: i) identification of repetitive damages and failures, classification by type of equipment or system; ii) identification of the causes of the failures; iii) collection of other information such as: repairing cost, mean time between failures (MTBF), mean time per failure (MTPF); iv) identification of previously utilized corrective actions.

2.3.2. Failure criterion

The gravity indicators referred by Aguilar-Otero, Torres-Arcique, Magaña-Jiménez [10], Moubray [11] and Scarpatti [12], were taken into account with the purpose of defining the gravity of the failure. These indicators mainly gather the specialized experience obtained in the analysis, treatment and consequences of the failures that typically affect the control and protection schemes.

2.3.3. Experimental design

The analysis and graphics results were obtained using the statistical package STATGRAPHICS Centurion XV (Trial version 15, StatPoint Inc., USA). A factorial design of experiments was used to study the effects of the quantitative factors in the design mathematical model defined as.

$$y_{ijk} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\beta\gamma)_{jk} + \\ +(\tau\beta\gamma)_{ijk} + \epsilon_{ijk} \begin{cases} i = 1,2,\dots,a \\ j = 1,2,\dots,b \\ k = 1,2,\dots,c \end{cases} \quad (1)$$

where the variables τ, β, γ represent the factors *engine*, *cylinder* and *working time*, and their interactions. A variance analysis methodology (Anova) was utilized for analyzing the levels of the factors, where an F value was calculated, for a probability of 0.05, and compared with a value in a table, in order to determine significant differences between the levels of the factors [13–15]. These were defined as follows: factor engine was set equal to 15, each *engine* with 9 *cylinders*, and the *working time* was considered as 3 years (2015-2017)

2.3.4. Measuring instruments

A *Digital Pressure Indicator* Leutert, model DPI-2, was utilized for measuring the injection pressure and combustion chamber temperature which was accumulated in each cylinder. This instrument enables determining the pressure and temperature when entering. The DPI system includes a sensor, to measure the injection pressure in diesel engines. The data obtained was processed and evaluated with the device software, version 3.24 for Windows®.

3. Results and discussion

In this section, the results obtained during the experimentation are presented and discussed.

3.1. Temperature analysis in the combustion chamber (cc) of the engines

Table 2 shows the measurements of combustion chamber temperature, of the 15 engines under study. The main *factors*, *engines*, *working time* and their *combination*, were highly significant with a probability of 95%, since the Anova p-values were smaller than the 0.05 limit.

These results indicate that there is a high variability in the energy delivery of the site, because the work done by the engines is not efficient; this has an influence on the capacity of delivering energy to the national network. Another factor that has significant influence is the working time of some engines, since this depends on the electrical demand. The working order and the amount of energy required, according to the demand, are obtained from the generation plant.

The working order refers to the number of engines and the operating percentage required to supply such demand. This situation also generates a variability in the working time of the set of engines, and thus an inefficient management of the technology. Another important aspect that has influence, is operating the engines under what is considered as optimal (below 70% of the efficient generation capacity).

The Anova (Table 2) also indicated significant differences in the interaction of the factors *engines* and *working time*. Figure 1 shows the interaction *working time* and *engines* as a function of the temperature in the combustion chambers. There is no defined trend showing an increase in the temperature of the individual engines during summer months (May to October), or a temperature decrease in the winter months (November to April).

This fluctuation in the temperature values is due to the maintenance carried out in each engine, and the variation in the physical properties of the fuel, according to the origin batch and the supplier [16]. This last aspect is very important, since it changes physicochemical parameters of the fuel, such as: viscosity, density, calorific value, coal percentage, asphaltenes and sediments, among others [17].

Table 3 shows a comparison of the mean values of temperature in the combustion chambers and homogeneous groups, between the levels of the factors engine and working time.

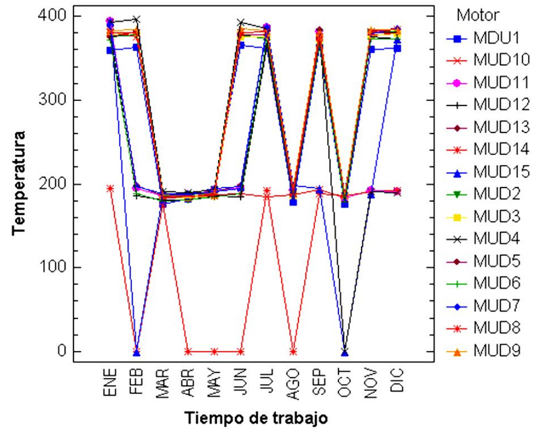


Figure 1. Interaction working time and engines as a function of temperature

Table 2. Anova Table for temperature of the combustion chambers

Source	SS[a]	GL[b]	CM[c]	F-Ratio[d]	p-value
ICE	$7{,}44.10^6$	14	$5{,}3.\ 10^5$	24,66	0,0000[e]
Cylinder	$3{,}92.\ 10^4$	8	4906,88	0,23	0,9860
Working time	$2{,}03.10^7$	11	$1{,}85.10^6$	85,68	0,0000[e]
ICE*Cylinder	$2{,}41.\ 10^5$	112	2157,18	0,10	1,0000
ICE*Working time	$1{,}06.10^7$	154	$6{,}9.\ 10^4$	3,18	0,0000[e]
Cylinder*Working time	$2{,}1.\ 10^4$	88	238,64	0,01	1,0000
RESIDUES	$6{,}18.10^7$	2865	$2{,}15.\ 10^4$		
TOTAL (CORRECTED)	$1{,}0.10^8$	3252			

Note: [a]SS. Sum of squares, [b]DF. Degree of freedom, [c]MS. Mean squares, [d]F-ratio: F-value for a probability 95 %, [e]Significant for a probability 95 %

It can be seen that there is no uniform distribution in the temperature observed in the 15 internal combustion engines (ICE) of the generation facility, indicating a wide range of average temperature which oscillates between 109 and 302 °C. This range of values is below the optimal value of 320 °C. On the other hand, it was observed a trend of the average global temperature of the ICEs to decrease in the months between November and March, which correspond to the coldest months; these results match the ones referred by [1, 10].

3.2. Analysis of the injection pressure in the engines

Table 4 shows the analysis of variance for the injection pressure as a function of the factors previously mentioned. The main factors ICE and *working time* remained significant, indicating that there are differences in the injection pressure among the 15 engines. This variability is mainly due to stops in the operation, which can be related with maintenance, technical revision, damages; or simply because there is no increase in demand, and some engines in the electrical plant are put out of service. The factor *working time* is also closely related to the variability of the injection pressure, since as the working time of the engine increases so does the wear of its components, and the feeding system aggravates due to the variation in the quality of the fuel [18].

No significant differences were detected among the cylinders of the engines, indicating that the fuel injection pressure within the combustion chamber is constant.

It can be observed in Figure 2, that the average values of global injection pressure of the generation facility were almost constant in most of the months. According to the *working time*, only a deviation was observed in the months of April and May. Similarly, the engines ICE1, ICE2 and ICE9 showed pressure increases compared to the rest of the engines. These increments may be caused by lack of relationship between the angle of the toothed bar, and the amount of fuel entering and clogs in the nozzles or in the fuel filters.

Table 3. Comparison of mean values of temperature in the combustion chamber and between the levels of the factors *engine* and *working time*

Engine	Mean (°C)	Homogeneous gropus	Working time	Mean (°C)	Homogeneous groups
ICE1	286,6±9,8	XXXX	ENE	172,9±8,9	X
ICE2	297,9±9,9	XXX	FEB	176,5±8,9	X
ICE3	296,8±9,9	XXX	MAR	177,1±8,9	X
ICE4	258,0±9,9	XX	ABR	369,0±8,9	X
ICE5	298,0±9,9	XXX	MAY	337,9±8,9	XX
ICE6	261,7±9,9	XXX	JUN	353,0±8,9	XX
ICE7	271,4±9,9	XXX	JUL	266,6±8,9	X
ICE8	299,4±9,9	XX	AGO	266,8±8,9	X
ICE9	302,6±9,9	X	SEP	340,8±8,9	XX
ICE10	250,2±9,9	XX	OCT	327,4±8,9	X
ICE11	239,6±9,9	X	NOV	159,8±8,9	X
ICE12	262,2±9,9	XXX	DIC	183,8±8,9	X
ICE13	271,9±9,9	XXXX			
ICE14	109,9±9,9	X			
ICE15	208,4±9,9	X			

Table 4. Analysis of variance for injection pressure

Source	SS[a]	GL[b]	CM[c]	F-Ratio[d]	p-value
Engine	32558,6	14	2325,6	2,19	0,0065[e]
Cylinder	5755,2	8	719,4	0,68	0,7119
Working time	28061,5	11	2551,1	2,4	0,0058[e]
RESIDUES	2,06E+06	1943	1062		
TOTAL (CORRECTED)	2,13E+06	1976			

[a]SS. Sum of squares, [b]DF. Degrees of freedom, [c]MS. Mean squares, [d]F-ratio: F-value for a probability 95 %, [e]Significant for a probability 95 %.

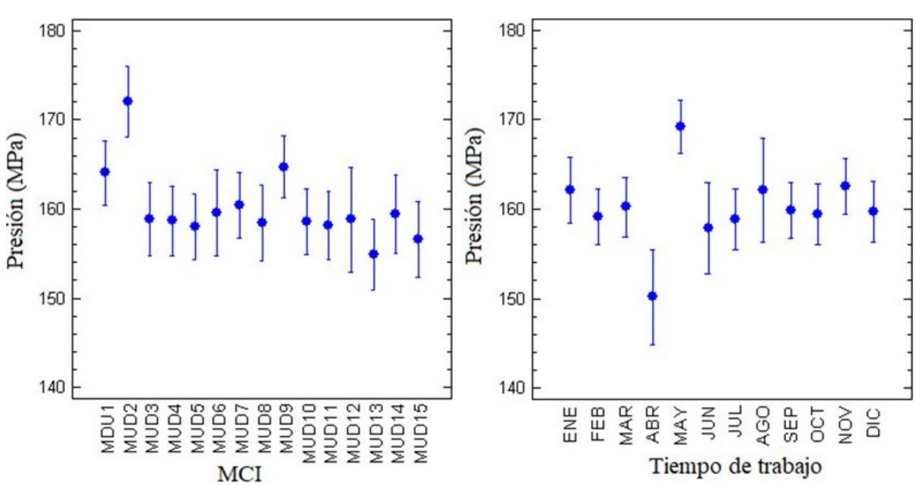


Figure 2. Representation of the ranges of mean pressure per engine and working time.

3.3. Analysis of failures by injection pressure and temperature in the combustion chamber

As observed in Figure 3a, the failures in 2015 were influenced by the high temperatures reached by the ICE of the generation facility. The ICEs 15, 9, 11 and 8, in that order, were the affected by the high temperatures.

This situation was due to various factors, which affected the electric generation capacity of the facility; among these factors, the *working time* and the *fuel quality* should be highlighted. A similar behavior was observed in 2016 (Figure 3b), where the failures due to temperature were greater than the failures due to injection pressure.

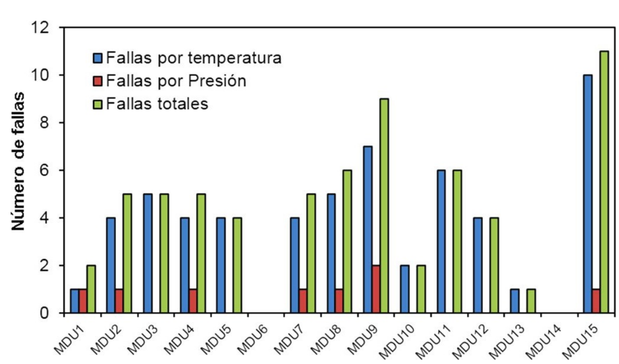
Nevertheless, a reduction in the number of failures can be seen in 2017 (Figure 3c); only the ICE8 had more failures, the remaining ICEs of the facility showed smaller values.

Compared with the previous years, this was the years of lowest incidence, demonstrating an improvement in the operation and efficiency of the facility, due to better knowledge and experience acquire by the operators, as well as an enhancement in the maintenance of the equipment.

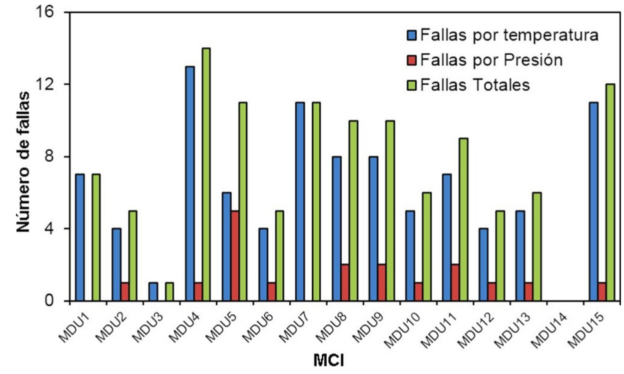
It can be seen in Figure 4 that the number of failures was reduced in 2018, due to the effects of injection pressure and temperature in the combustion chamber in some ICEs of the facility. This is due to the better management of technology during this period.

Therefore, there were no anomalies in the operation of the facility and energy delivery to the national electrical network. However, failures were reported in some ICEs, such as ICE2, ICE4, ICE8, ICE11, ICE13 and ICE15, with ICE2 and ICE13 having higher incidence with 6 failures in this period. These results indicate a better working efficiency of the generation group.

However, although the number of failures was reduced, it should be sought to optimize the generation of the facility, focusing in improving the efficiency of the operating methods and the decisions of the Board of Directors [19].



a)



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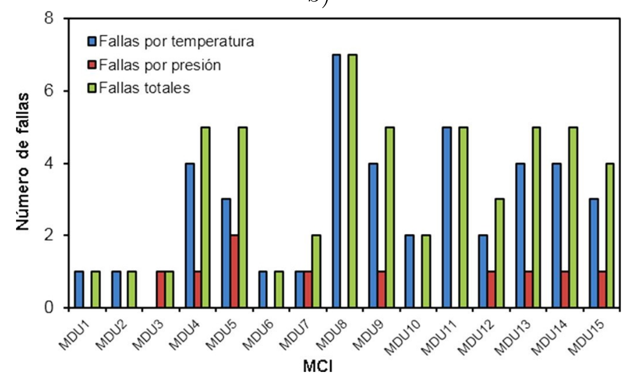


c)

Figure 3. Summary of failures due to pressure and temperature a) 2015; b) 2016; c) 2017.

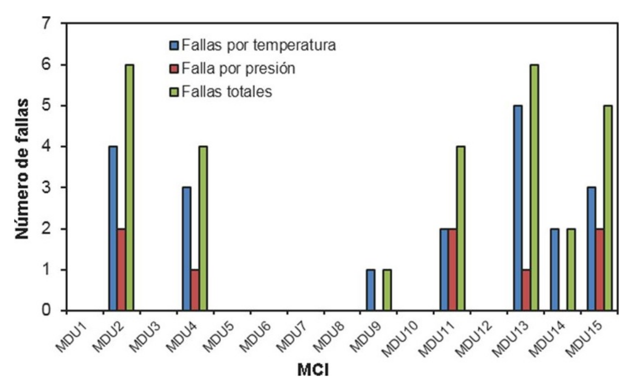


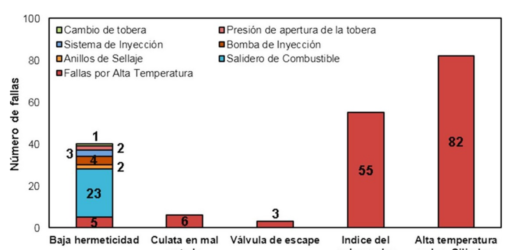
Figure 4. Summary of failures due to pressure and temperature in 2018.

Figure 5 shows the total failures caused by injection pressure and temperature in the combustion chamber, in the period 2015-2017.

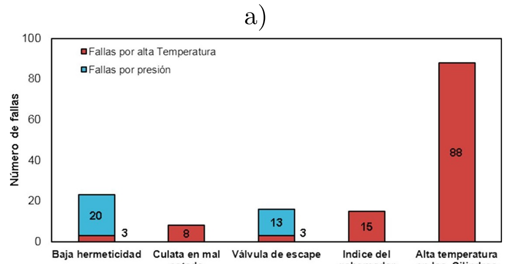
During 2015 (Figure 5a), the greatest number of failures was due to high temperature (82 failures), which is directly related with the governor index (55 failures). The «governor» gives the opening angle of the toothed bar, i.e, the accelerator. A high index indicates an increase in the acceleration of the engine, which during a long working period causes high temperatures and pressure in the cylinders [20–22]. A high governor index in conjunction with an inadequate operation of the injector, may cause high temperatures in the cylinders because it enables the control of the index of the toothed bar and the fuel input [23]. When injectors operator inefficiently, the fuel input to the cylinder increases, and thus the temperature increases due to excess of fuel in the combustion chamber [2]. This phenomenon also generates black residual gases [24].

The third most detected failure were the fuel outlets (23 failures). This phenomenon is directly related with a deficient sealing in the feeding system, due to an inadequate maintenance and revision of the ICE. However, in 2016 various failures observed in 2015 were corrected (Figure 5b). No failures due to sealing were detected in the feeding system, the number of failures in the governor index was reduced 72%, but the number of failures due high temperatures remained large (88 failures); the other indicators reported a range of failures between 5 and 20. In 2017 (Figure 5c) the number of failures due to high temperatures in the cylinders was reduced (64 failures), but there was an increase in the number of failures in the governor index (44 failures) and low hermetism (7 failures).

Figure 6 shows the behavior of the ICEs in 2018. The failures due to high temperatures exhibited the highest incidence (21 failures), even though it was observed a decreasing trend with respect to previous years.



a)



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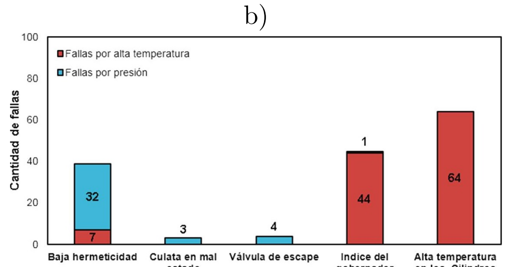

c)

Figure 5. Most significant failures caused by pressure and temperature, and their effects on the ICEs 9H21/32: a) 2015; b) 2016; c) 2017.

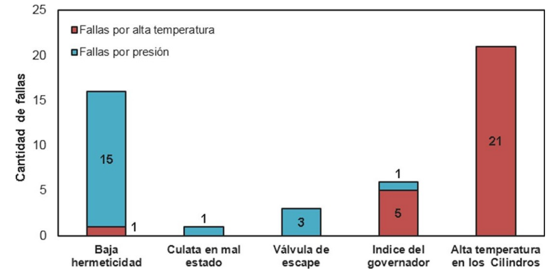

Figure 6. Most significant failures caused by injection pressure and temperature in the combustion chamber in 2018.

4. Conclusions

The analysis demonstrated that the injection pressure and the temperature in the combustion chambers are indicators that influence the occurrence of failures in the 1.7 MW Hyundai ICEs.

The number of detected failures due to temperature in the combustion chamber are significantly higher, compared to the failures reported due to injection pressure.

In general, such high temperatures are related with a high governor index and a deficient operation of the injectors.

The interaction of the factors ICE*working time was statistically significant in the analysis of the temperature in the combustion chamber, producing an inefficient operation of the ICEs and the energy delivered by the facility.

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