Design Optimization to Reduce Corrosion in Electric Flex Fuel Pump

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ABSTRACT

By the 2nd law of thermodynamics for metal oxidation, it is known that corrosion cannot be avoided, but mitigating it is essential for the safety and protection of people and of the environment. In the automotive industry, one of the components most susceptible to corrosion is the fuel pump due to its electrical operation and direct exposure to fuels. This situation can lead to electrochemical corrosion and, consequently, it can contaminate the vehicle fuel supply system. With the growing incentive to use ethanol and hence the flex fuel pumps, this scenario should be focus of attention due to the properties of ethanol. This work focuses on investigating the root cause of a characteristic corrosion appearing on the fuel pump housing in durability tests. Based on the theory of electrochemical corrosion, the influence of an exposed and unused grounding terminal of the fuel pump electrical connector is proved and its removal is proposed to mitigate the corrosion. After conducting a durability test with aggressive ethanol and at high temperature on samples with and without the grounding terminal, it is found that the proposed design significantly improves the housing protection against corrosion and corroborates with the electrolysis theory.

INTRODUCTION

As described in [1], to produce a metal from minerals and ores, it is necessary to provide a certain amount of energy. Upon its formation, metal assumes a temporary form, as it tends to revert to its original form after exposure to the environment and interaction with other elements. Because of this naturally occurring process, achieving absolute prevention of corrosion is impossible, but controlling it is essential.

IMPACTS OF CORROSION IN THE AUTOMOTIVE INDUSTRY – Within the automotive industry, corrosion stands as a persistent and long-standing concern due to its potential to impact customer safety, environmental protection, product aesthetics and resale value, if left unmitigated. Moreover, the expenses associated with maintenance and repair of corroded components make corrosion even more undesirable. In the early 2000s, a 2-year study conducted by the U.S. Federal Highway Administration (FHWA) unveiled that the annual estimated cost of corrosion in the transportation category was $29.7 billion, with motor vehicles accounting for 79% of this sum [2]. Given the subsequent economic growth and rising price inflation experienced in the U.S., it is plausible to expect that these costs have significantly increased.

Despite the existence of established solutions against corrosion, such as coatings, the reappearance of this issue from time to time is common due to progress and changes in products, markets, materials, environment, among other factors. With the growing incentive for decarbonization, the increase in the adoption of biofuels is already a reality and should be focus of attention regarding protection against corrosion.

ETHANOL AS FUEL – In Brazil, the main hope for decarbonization lies in the use of ethanol as fuel. Despite being a pioneer on using ethanol as a fuel and being one of the largest consumers and the second in production [3], Brazil still does not adopt ethanol as the first choice when refueling, with gasoline still being the most preferred. This can be attributed to the price difference favoring gasoline over ethanol across most Brazilian states [4]. Nevertheless, in the upcoming years, this scenario is expected to change, driven by the evolving tendency of regulatory agencies to impose more stringent emission limits.

Predicting the increase in the use of ethanol as the main fuel in Brazil, the protection of automotive components against corrosion will become a target for improvements. From Table 1 [5], the high conductivity and the substantial percentage of water content give ethanol characteristics that make it more corrosive in comparison to common gasoline.

Further compounding this concern, as noted in [6], is the adulteration of fuel, frequently found at Brazilian gas stations. In the case of ethanol, due to its miscibility with water, adulteration is carried out by adding water to it, which consequently leads to an increase in the conductivity of the fuel.

Table 1. Hydrated ethanol specification reference

Characteristics	Unit	Limits Min	Limits Max	Methods
pH @ 20°C	-	6	8	NBR 10891
Specific mass @ 20°C	kg/m³	805,2	811,2	NBR 5992 NBR 15639 ASTM D4052
Alcohol content	% m/m	92,5	94,6	NBR 5992 NBR 15639
Conductivity	μS/m	-	300	NBR 10547 ISO 17308
Acidity level	mg/L	-	30	ISSO 1388-4
Aldehyde content	mg/L	-	60	EM 15721
Higher alcohol content	mg/L	-	500	ASTM D1617
Ester content	mg/L	-	100	NBR 8644
Evaporative residue	mg/100ml	-	5	NBR 10894
Sulfate content	mg/kg	-	4	NBR 10422
Sodium content	mg/kg	-	2	NBR 13993
Hydrocarbon content	% v/v	not detected		NBR 16041
Methanol content	% v/v	-	0,5	NBR 16041
Ethanol content	% v/v	94,5		NBR 16041 ASTM D5501
Water content	% m/m	-	7,5	NBR 15531 NBR 15888 ASTM E203
Organ: Ministry of Mines and Energy/ National Petroleum, Natural Gas and Biofuel Agency Resolution n° 764, 12/20/2018				

FUEL PUMP – Several automotive components, including the electric fuel pump, are susceptible to the corrosiveness of fuels. As described in [6], the fuel pump is placed inside the Fuel Supply Module (FSM), which has the function to continuously deliver fuel from the tank to the engine. The main function of an electric fuel pump is to generate flow by converting electrical energy into hydraulic flow. Within the Brazilian market, a fundamental requirement for this component is to operate with both gasoline and ethanol, as well as any intermediate blend thereof. [6].

ELECTROLYSIS – Due to its direct exposure to fuel and electrical operation, the fuel pump is inherently vulnerable to electrochemical corrosion. As defined in [1], an electrochemical reaction is a chemical reaction involving the transfer of electrons. This reaction can be spontaneous, denoted as an electrochemical cell, in which electrical energy is generated from chemical energy, or it can be non-spontaneous, denoted as electrolysis, in which electrical energy is converted to chemical energy.

In aqueous electrolysis, the focus of this work, four main elements are observed:

- Anode: surface where the oxidation reactions occurs and where corrosion is verified.
- Cathode: protected surface where the reduction reactions occurs and where there isn’t corrosion.
- Electrolyte: conductive solution or ionic conductor that simultaneously surrounds the anodic and cathodic areas.
- Electric potential difference between anode and cathode.

According to [1], in the presence of an electric potential difference between the electrodes, the positive ions, referred to as cations, are attracted towards the negative electrode, known as the cathode, while the negative ions, referred to as anions, are attracted towards the positive electrode, known as the anode. As the cathode attracts cations, it undergoes reduction by gaining electrons, while the anode becomes oxidized upon the attraction of anions and electrons loss. The oxidation reactions that occur at the anode cause what is known as corrosion. Figure 1, extracted from [7], illustrates this process.

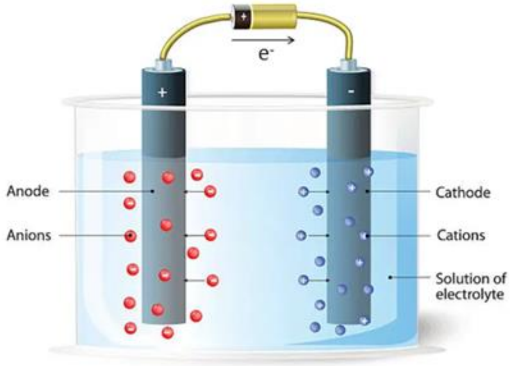

Figure 1. Electrolysis system

FUEL PUMP HOUSING – As it works through an input voltage and has several metallic components, the fuel pump can be subject to corrosion caused by electrolysis. One of the most susceptible components to this phenomenon is the fuel pump housing, which can be seen in Figure 2. The main functions of the fuel pump housing are:

- Ensure the internal sealing so that there are no leaks during the operation of the fuel pump.
- Fix the components inside of the pump.
- Ensure magnetic flux.

Figure 2. Fuel pump housing

Despite the fact that no field failures resulting from fuel pump housing corrosion have been reported, the appearance of corrosion during durability tests with aggressive ethanol is known, as depicted in Figure 3. Even though corrosion is expected, as these are tests that aim to stress the fuel pump, the distinctive pattern and concentration of corrosion observed on the housing are unexpected. It can be observed from Figure 3 that there are corrosion points along the entire housing, but also a corrosion accentuated in a specific region, located at the upper side.

Figure 3. Corroded housings in durability tests

GROUNDING TERMINAL - Near this corroded region, there is an exposed grounding terminal, delineated by a red circle in Figure 3, which maintains an electrical connection with the negative wire of the electrical connector. The main functions of the electrical connector are:

- Supply electrical energy from FSM flange until fuel pump.
- Conduct current draw from FSM flange until fuel pump.
- Reduce electromagnetic transient emission during the pump working time.

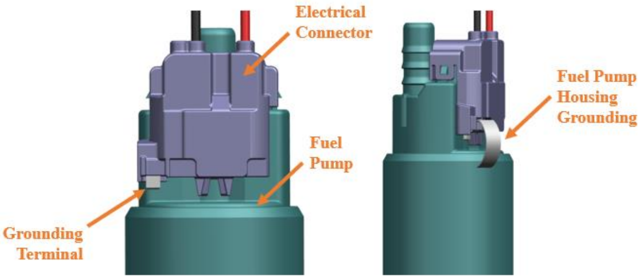

Figure 4. Electrical connector and the grounding terminal

As shown in Figure 4, the function of the grounding terminal is to ground the fuel pump housing. This function is used only for gasoline applications with ethanol content lower than 10%. In such cases, the presence of any spark or electrical discharge resulting from the accumulation of electrostatic charges on the housing may lead to ignition and compromise the safety of the vehicle and people. This requirement, established in [8], is graphically represented in Figure 5.

For gasoline applications with ethanol content higher than 10%, such as Brazilian gasoline, the grounding function is not required due to higher conductivity of the fuel, which eliminates the concern of ignition by facilitating the flow of ions through the fuel and consequently avoiding the appearance of sparks and electrical discharge that could lead to ignition.

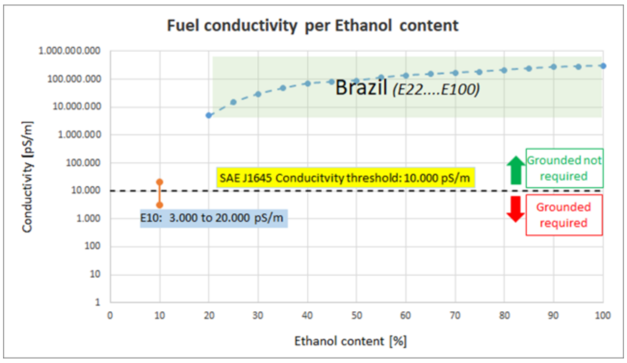

Figure 5. Grounding function requirement

Although there seems to be no problem keeping the grounding terminal exposed and unused, it forms an electrolysis system together with the fuel and the fuel pump housing during the fuel pump operation, as illustrated in Figure 6.

The electrical connection between the grounding terminal and the negative wire of the electrical connector, combined with the accumulation of electrostatic charges on the fuel pump housing, generates a potential difference between these two elements. The proximity of the grounding terminal to the housing and the potential difference between them establishes a conducive pathway for the transfer of positive ions from the housing to the grounding terminal, which leads to corrosion on the housing, as previously explained.

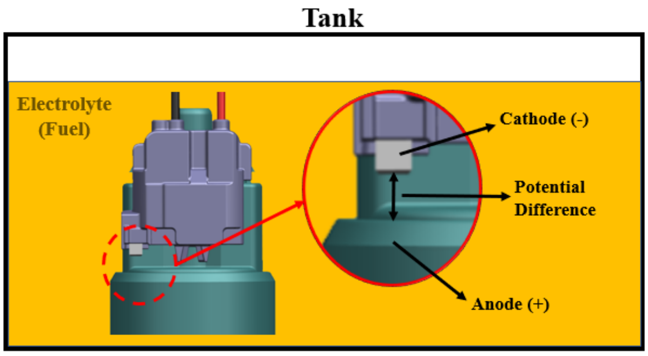

Figure 6. Electrolysis system formed by the fuel, grounding terminal and fuel pump housing.

Based on the theory of electrolysis, this work aims to investigate and prove the influence of the grounding terminal of the electrical connector on the corrosion observed on the fuel pump housing and proposes its removal to mitigate it. Furthermore, this work proposes a novel methodology for quantifying corrosion from fuel pump housing images.

The paper is structured in the following way: the experimental procedure describes the methodology of the test; the results show the comparison between the proposed and the current design regarding corrosion on the fuel pump housing. Finally, the conclusion evaluates the influence of the grounding terminal in the housing corrosion.

EXPERIMENTAL PROCEDURE

SAMPLES – To evaluate the impact of the grounding terminal on the fuel pump housing corrosion, electrical connector samples without this terminal were produced, as depicted in Figure 7. Furthermore, to mitigate potential variations due to the assembly process that could potentially influence the final outcome, it was ensured that both the electrical connectors and the fuel pumps used were from the same production batch.

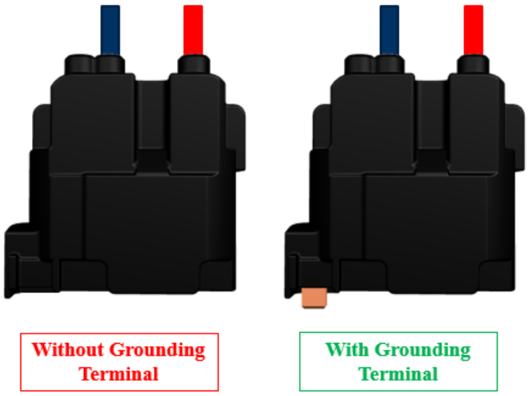

Figure 7. Sample configuration types

Considering the constraint imposed by the test bench, which can accommodate a maximum of six parts in a single durability test, three parts were subjected to the test for each sample configuration type. For the sake of standardization, samples denoted by numbers 1 to 3 will represent the parts without the grounding terminal, while samples designated by numbers 4 to 6 will correspond to the parts with the grounding terminal, as defined in Table 2.

Table 2. Samples identification

Sample	Configuration
1	Without grounding terminal
2	
3	
4	With grounding terminal
5	
6	

TEST SET-UP – A fuel pump durability test is a type of test conducted on a fuel pump to assess its ability to withstand and perform reliably under various operating conditions over an extended period. During the test, the fuel pump is subjected to a series of rigorous and controlled conditions which simulates the operating scenarios that it would encounter in the field.

In general, during the validation process of new fuel pumps, durability tests are executed to simulate the normal operating conditions encountered by the fuel pump within a vehicle. However, there are also durability tests with specific conditions that aim to accelerate failure modes. To accelerate the appearance of corrosion in fuel pump components, for example, specific durability tests were developed. For the present study, a durability test was conducted, employing the parameters outlined in Table 3.

Table 3. Test parameters

Parameter	Value
Input Voltage [V]	13,5
Pressure [kPa]	530
Temperature [°C]	60
Duration [h]	500
Cycle	8h ON, 16h OFF
Fuel	Aggressive ethanol

Although other test parameters are important to accelerate corrosion, such as input voltage and temperature, fuel is the main component of the corrosion system. The fuel used, hereafter denoted as aggressive ethanol, consists of ethanol with the addition of contaminants in order to make it highly corrosive. The specific reagents employed to create the aggressive ethanol formulation are detailed in Table 4.

Table 4. Aggressive ethanol reagents

Reagent	Formula
Zinc sulfate heptahydrate	$ZnSO_4 \cdot 7H_2O$
Sodium sulfate	Na_2SO_4
Sodium chloride	$NaCl$
Manganese chloride	$MnCl_2 \cdot 4H_2O$
Ethyl acetate	$CH_3COOCH_2CH_3$
Acetaldehyde	CH_4O
Acetic acid	CH_3COOH

As previously described, a single durability test accommodates a maximum of six parts. Therefore, all parts were subjected to the test under identical test conditions, thus eliminating any possible bench, fuel or test parameter variations. Furthermore, at regular intervals of 168 hours, images of the fuel pump housing were captured, while fuel samples were obtained for pH and conductivity analysis. This effort aimed to verify the relationship between the progression of these properties and the observed corrosion.

CORROSION MEASUREMENT – To quantitatively assess corrosion based on the images captured during the durability test, image processing techniques were employed. The underlying objective of this processing methodology is to quantify the extent of corrosion by determining the percentage of corroded area relative to the total area of the fuel pump housing.

To accomplish this, the Python programming language [9] and the OpenCV library [10] were employed. The methodology will be explained using the corroded housing in Figure 8 as an illustrative example. In order to simplify the corrosion quantification process, only images capturing the side of the housing containing the grounding terminal were considered. This delimitation is reasonable as the opposing side typically exhibits minimal or no corrosion. Therefore, when referring to the housing area, it should be understood as the area on the side of the housing where the grounding terminal is located.

Figure 8. Original image

The initial step involved the isolation of the housing from the surrounding image, as exemplified in Figure 9. By obtaining the housing image with a transparent background, it became possible to estimate the housing area. To achieve this, the alpha channel was extracted. Together with the red, green and blue (RGB) channels, these four define the colors of an image. While the RGB channels define the colors themselves, the alpha channel represents the level of transparency for each pixel of the image, including the background pixels. Its values range from 0 to 255, where 0 represents full transparency and 255 represents no transparency. Therefore, the number of pixels with an alpha channel value greater than zero was considered as an estimation of the housing area.

Figure 9. Isolated housing

To estimate the corroded area, the RGB color space was converted to the HSV color space. The decision to convert the color space to HSV was motivated by the separation of brightness information from color information, which facilitates color identification tasks, particularly in scenarios where environmental lighting poses challenges, such as in metallic surfaces. The Figure 10, extracted from [11], illustrates this separation.

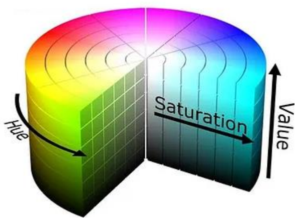

Figure 10. HSV color space

In the HSV color space, a color range was established to define the criteria for identifying corrosion. For this, a color was defined as a lower limit, representing the darkest color, and a color as an upper limit, representing the lightest color. With this range of colors, a new image was then produced, denoted as a mask, in which all pixels falling outside this defined color range were assigned a zero value. The Figure 11 shows the mask applied in Figure 9.

Figure 11. Corroded regions

Using the acquired mask, the contours corresponding to the corrosion spots in Figure 9 were identified employing the technique defined in [12]. The Figure 11 illustrates the contours found for the example image. Subsequently, the area of each contour was calculated, and the cumulative sum of all contour areas served as an estimation of the corroded area. With the housing area, initially found, and the estimated corroded area, the percentage of corroded area could be computed. This percentage will be used in the results section to facilitate a comparative analysis of the corrosion progression across the different parts.

Figure 12. Contoured image

RESULTS

As described in the preceding section, at regular intervals of 168 hours during the durability test, images of the fuel pump housing were captured. The chart in Figure 13 shows the percentage of corroded area of the fuel pump housing as a function of test time for each part. The percentage of corroded area was calculated based on the methodology proposed in the previous section.

The chart reveals a clear contrast between the parts with the terminal, represented by the red color, and without the terminal, represented by the blue color, showing that the terminal has influence on the corrosion of the pump housing and validating the proposed theory. By eliminating the grounding terminal through the process of cutting and capping, the passage of ions is either blocked or substantially attenuated.

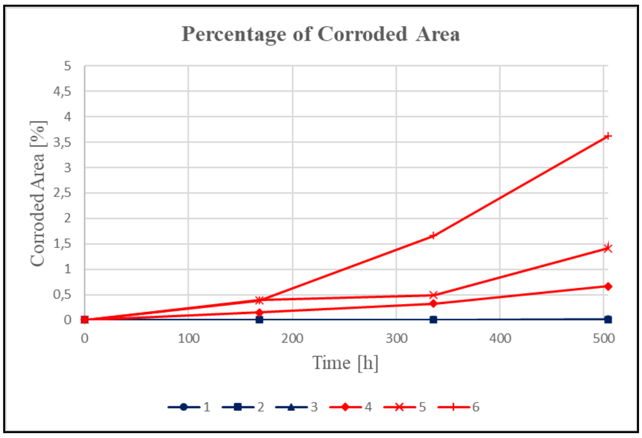

Figure 13. Percentage of corroded area per test time

Figure 14 demonstrates that while the pH remained relatively stable, the conductivity exhibited a significant increase. This can be attributed to the fact that corrosion products, such as metal ions, may have dissolved in the fuel and contributed to the increase in conductivity. A metal ion in solution can act as a charged particle in motion, thus favoring the transmission of current through the solution and consequently increasing its conductivity.

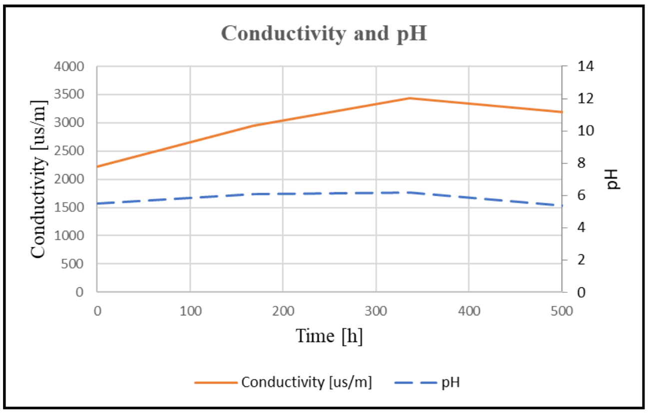

Figure 14. Sample configuration

Based on Figure 15, it is evident that corrosion in the parts containing the grounding terminal initially concentrates in the region close to the terminal and gradually spreads over time. One aspect that potentially contributed to the increase in corrosion was the increase in fuel conductivity during the test.

CONCLUSION

Through this work, the influence of the grounding terminal of the electrical connector on the corrosion of the fuel pump housing in durability tests was proven. It was seen that the two elements, together with a conductive fuel, form an electrolysis system. Furthermore, based on the observed results, this work proposes the removal of the grounding terminal for the applications in which the ethanol content of gasoline is higher than 10%, concluding that it is harmful for the product.

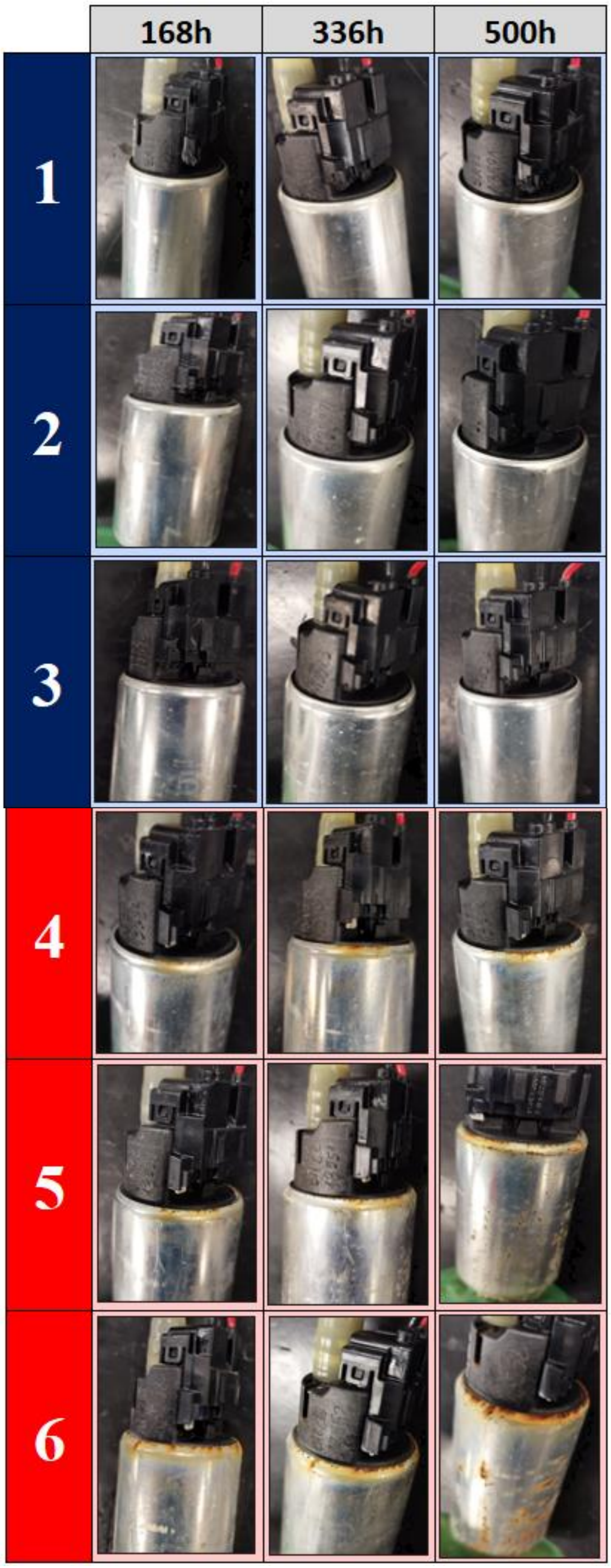

Figure 15. Images of the fuel pump housing captured during the test

Due to its lack of usability in Brazilian applications and the tendency to increase the use of ethanol for decarbonization purposes, maintaining the grounding terminal could favor the appearance of corrosion, mainly in adulterated ethanol.

In order to simplify the corrosion measurement during the test and reduce the test duration, a corrosion quantification methodology based on image processing techniques was proposed. A robust comparison of the obtained measurements with the images of the housing revealed that the estimated corrosion progression effectively represented the actual corrosion evolution in the parts throughout the duration of the test.

The findings in this work open up avenues for future research and investigation. Further studies could focus on characterizing the relationship between the distance from the grounding terminal to the housing and the corrosion rate. Also, understanding the effects of varying environmental conditions, such as temperature, input voltage and impurities in the fuel, on the corrosion would enhance our understanding of the corrosion process and help to design more corrosion-resistant systems.

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