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A predictive model for life assessment of automotive exhaust mufflers subject to internal corrosion failure due to exhaust gas condensation

M.H. Nazir [a,*], Z.A. Khan [a], A. Saeed [a], K. Stokes [b]

[a] Bournemouth University, NanoCorr, Energy and Modelling Research Group (NCEM), Faculty of Science and Technology, BH12 5BB, UK
[b] Defence Science and Technology Laboratory (DSTL), Ministry of Defence (MoD), Salisbury, UK

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ABSTRACT

A study has been presented on pitting corrosion on internal walls of automotive exhaust muffler due to exhaust gas condensation. The problem mainly exists in the rear section of the exhaust system close to the tail end pipe such as the muffler, especially when the temperature of the muffler does not go up during short distance run or winter. The water vapour condenses on the muffler's inner wall in the form of water droplets. The dissolution of corrosive gases coming from the internal combustion of engine as well as condensation of low-pH acidic vapours in the water droplet can cause severe pitting corrosion on standard exhaust steel. In this work, an experiment is reported for internal corrosion, by using mufflers as test bed subjected to different environmental conditions. Based on observations, a mechanistic model has been developed which involves three main techniques: (i) the dropwise condensation technique predicts the condensation rate and is based on heat and mass transfer theory, (ii) the species breakdown in the droplet is established through the main thermodynamic and chemical equilibrium, and (iii) the pitting corrosion involving pit depth is predicted using electrochemical kinetic reactions, species transport and chemical reactions occurring inside the droplet. Lastly, the accuracy of the model has been validated by comparison between experimental and predicted results showing good agreement.

1. Introduction

Modern automotive exhaust systems consist of several individual sections from the engine side to the tail end pipe. The material properties of these sections directly relate to the operating temperature to which each section is subjected, ranging from 600 to 900 °C near the engine (hot section) to 100–350 °C for parts situated at a distance from the engine such as mufflers and tail end pipe (cold section) [1].The material properties of exhaust required for the hot section include high-temperature strength, thermal fatigue properties, oxidation resistance and salt corrosion resistance. While those required for the cold section away from the engine is corrosion resistance to salt damage and exhaust gas condensate. The corrosion problem is mostly observed during-short distance driving, when the temperature does not increase and wet corrosion due to condensation mainly in the muffler at the cold end becomes the major factor of failure [2].Typical types of corrosion mechanisms observed in exhaust systems include general corrosion, pitting corrosion, crevice corrosion, inter-granular corrosion, oxidation, etc. Corrosion failures may cause perforation of components causing exhaust leaks in internal components that may result in noise issues due to change in muffler acoustics and can also result in pollution causing damage to environment. Perforation can be a small area due to localised corrosion such as pitting in which pits can penetrate the material thickness [3].

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[*] Corresponding author.

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Pitting corrosion is one of the major problems due to which automotive exhaust components have a limited lifetime as it is basically attacking the muffler for a long time. Even stainless steel does not possess effective corrosion resistance due to very highly aggressive environment. The resistance of different steel grades to pitting corrosion can generally be compared on the basis of their alloy composition via their pitting resistance equivalent number, PREN [4]. However, this is questionable for the special conditions existing in automotive exhaust systems, with their frequent wet/dry alternation and their short operating times compared with overall life cycles [5]. The important area of research is not only in the selection of material for maximum resistance to the onset of pitting corrosion but also on how the pitting can be monitored as well as predicted using state of the art condition monitoring technique. This technique if incorporated in the muffler design of modern automotive applications e.g. cars can help prevent early failures of exhaust systems under wet conditions.

A literature survey shows that the major part of studies on corrosion performance of stainless steel exhaust mufflers covers experimental techniques to analyse the effects of exhaust gas condensates [6–11] and the muffler's material selection [12–18]. In terms of acoustic modelling, many design models to reduce muffler noise exist [19–22], however predictive modelling techniques for corrosion failures of exhaust mufflers due to exhaust gas condensation [23–26]and material selection [27]are extremely rare and little can be found within the existing literature. Therefore this research has been conducted to fill the knowledge gap in this area of critical significance.

This research focusses mainly on wet corrosion of automotive exhaust mufflers at the cold end. Wet corrosion of inner muffler wall due to gas condensation is one of the major causes of muffler failure [5].The condensation of water droplets and dissolution of corrosive gases in droplets act as a major medium for internal corrosion of mufflers incorporating high contents of carbonate ions, sulphate ions, nitrate ions and chloride ions which constantly accumulate as the engine repeatedly starts and stops [28].This condensation process produces carbonic acid, sulphuric acid, nitric acid and low levels of hydrochloric acid, creating critical conditions with acidic pH-values which act as an ideal medium for pitting corrosion on standard exhaust steel [29]. Various stainless steel grades which are highly resistant to pitting are used by manufacturers in muffler design however they are also much more expensive compared to conventional basic steel [30]. It is still difficult to predict the long term behaviour of corrosion resistant stainless steel when subjected to real environment besides their good corrosion prevention properties. For internal muffler corrosion, a vast literature has been available mainly focussing on material selection for designing highly corrosion resistant mufflers [1,31–36] however, there are grey areas that need to be researched more in terms of developing predictive modelling techniques to address early failure issues of mufflers due to exhaust gas condensation and corrosion. These predictive models can be utilised by manufacturers to design durable, high strength and corrosion resistant exhaust mufflers.

Our previous research has modelled [37–48,65] corrosion on metal surface (pitting and uniform) as a result of coating failure. However, the aim of this research is to develop a mechanistic model for exhaust mufflers which is able to predict the condensation rate of water droplets as well as species breakdown in droplets and pitting rate including pit depth. Condensation happens when the temperature of the muffler does not go up compared to that of the saturated vapour flowing inside the muffler. The water vapour in the gas phase condenses on the muffler's inner wall in two different ways: (i) bottom of the muffler condensation happens when the condensed liquid on the side walls of the muffler slides to the bottom due to gravity and forms a pool of liquid at the base, and (ii) top of muffler condensation happens when the liquid droplets nucleate, grow, detach and then fall due to gravity from the top wall of the muffler. The dissolution of corrosive gases coming from the internal combustion of the engine in the droplet can cause severe pitting corrosion. The area of the muffler that is most critical and prone to pitting corrosion is the top wall where condensation in the form of low pH acidic droplets directly takes place.

This paper discusses a detailed experimental study which was conducted by using mufflers as test bed. These mufflers were subjected to different types of exhaust gas condensates (like petrol and diesel) and were tested for different conditions such as wall temperatures, gas temperatures and gas velocities. Corrosion sensors and condensation sensors which were installed on the inner wall of the muffler were used to monitor corrosion rates and condensation rates respectively. Based on the observations recorded from experimentation, a holistic model was developed in which the chemistry inside the droplet was computed from the thermodynamic equilibrium at the interface of liquid gas and the electrochemical activity at metal surface related to the corrosion process. In the holistic design, a mechanistic corrosion model was combined with the drop wise condensation model to predict internal muffler corrosion due to exhaust gas condensate. Finally, the model was validated by qualitative comparison between experimental and predicted results showing good agreement between the two.

2. Experiment

2.1. Experimental setup

Three exhaust mufflers: muffler 1, muffler 2 and muffler 3 of similar dimensions and material properties fabricated using stainless steel were used as test samples. Muffler 2, at the start of experiment, was kept in low concentration sodium chloride (NaCl) solution at 20 °C, 0.65 M of NaCl dissolved in 11.1 M deionised water for 48 h while muffler 3 was kept in high concentration NaCl solution at 20 °C, 0.95 M of NaCl dissolved in 11.1 M deionised water for 48 h. Muffler 1 was only subjected to deionised water at 20 °C for 48 h. The sample mufflers were then removed and their inner side was air dried to allow chloride ions to deposit on the inner wall. The step was performed to simulate and analyse the effect of road salt on the corrosion of the mufflers' inner wall.

Next, in order to perform the real time measurements of condensation rate and corrosion rate, the mufflers' top cap was removed and the inner wall of each muffler was installed with a condensation sensor having dimensions 45 mm × 20 mm