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RESEARCH ARTICLE

INVESTIGATION OF FAILURE MODES OF EXHAUST GAS RECIRCULATION (EGR) SYSTEM

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ABSTRACT

The exhaust gas recirculation (EGR) system is widely used heat exchanger to meet the emission standard as specified by Euro norms And BS norms. The coolant passes through the shells to cool down the exhaust gas inside the tubes. Mainly EGR system is used to control the Oxides of nitrogen (NOx) emission. The emission reduction is an important task in the development of an internal combustion engine. To limit these emissions it is essential that EGR system should work in safe mode without damage. But due to improper design and manufacturing, failure of EGR system occurs. Such failure leads to increase in Emission level, which affects the environment. Therefore, it is necessary to investigate the probable causes of EGR system failure and find out the techniques for elimination of that failure. It will involve the inspections and finite element analysis (FEA) of the EGR cooler system for detection of failure. This work deals with investigation of failure causes and to provide feasible solution to reduce that failure.

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INTRODUCTION

In recent years, stringent emissions legislation has been imposed worldwide on nitrogen oxide (NO_x), carbon di-oxide (CO_2), hydrocarbons (HC), and particulate matter (PM) emissions from internal combustion engines (IC) engines. These emissions impose a major threat to the environment, in terms of global warming and carcinogenic particles(Abd-elhady *et al*., 2011). Emission reduction is an important task in the development of internal combustion engines. Exhaust gas recirculation (EGR) is a nitrogen oxide emission reduction technique used in internal combustion engines. EGR works by recirculating a portion of the engine's exhaust gas back to the cylinders. Mixing the incoming air with recirculated exhaust gas dilutes the inert gas concentration, and hence lowers the flame temperature. NO_x is formed at very high temperature which is about 1370 centigrade (˚C) or higher, EGR serves to limit the generation of NO_x(Yansong Wang *et al*., 2008). Currently the automotive industry frequently faces new challenges as the demand increases for inexpensive and at the same time, high quality components. Extreme care must be taken to ensure that such components are designed and manufactured with sufficient quality to withstand a variety of service environments. However, due to material defects, improper design components for the service environment can lead to failure.

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If a failure occurs in such a component, a very careful and precise approach is necessary to identify the failure root cause and to make appropriate design and manufacturing changes in order to prevent failure. Generally investigating the entire background information is important before inspecting failed components. In that, material composition, specification requirements, manufacturing history, heat treatment, operation and service history included(Pravin S. Salunkhe and Dhummansure, S. R. Babar, 2015). This paper gives the basic information of various modes of EGR cooler failure such as fouling, boiling, corrosion, failure due to mechanical stresses and thermal stresses and techniques to lower these failures. Fouling block the flow of exhaust gas causes failure of cooling coils, boiling in EGR cooler is not good for its proper working, corrosion leads to total system failure, due to mechanical and thermal stresses there is failure of brackets, cooling coils and bellow pipe of exhaust gas recirculation (EGR) system.

Introduction to EGR components

Housing: Housing is protective covering of EGR cooler. Housing is part of core which take entire load and vibrations of system.

Bellow pipe: Bellows are used in piping systems to absorb thermal expansion or terminal movement where the use of expansion loops is undesirable or impractical.

Diffuser: The purpose of diffuser to guide the entry and exit of exhaust gas and maintained the smooth flow of exhaust gases at entry and exit.

Header: Mainly headers are used to hold the winglet tubes. Components of EGR are shown in Figure 1.

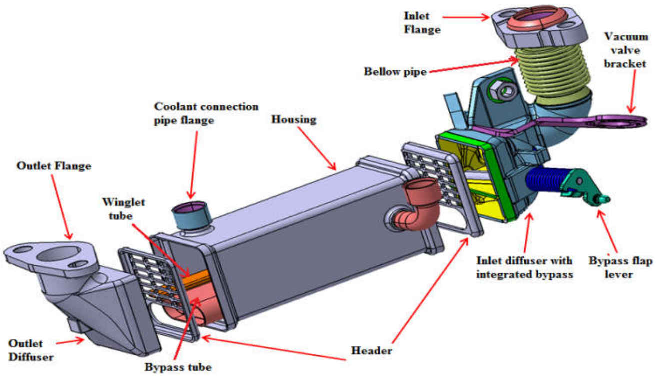

Figure 1. Components of EGR (Pravin Salunkhe *et al.*, 2015)

Modes of Failure

The failure of Exhaust Gas Recirculation (EGR) system is mainly due to fouling, boiling, corrosion, mechanical stresses and thermal stresses.

Fouling failure

The formation of insulating layer that adds thermal resistance is known as fouling. Fouling is nothing but increase in particulate matter (PM). Thermophoresis and turbulence in the flow are main mechanisms in for particulates transport to tube wall. Flue gas particles experiences force in the direction of cooler surface due to temperature gradient between the combustion gas and heat exchanger surface, this effect is known as Thermophoresis. Fouling of system stabilizes after certain period (about 42 hrs.) (Abd-elhady *et al*., 2011); this is known as asymptotic behavior of fouling. It is causes due to the sintering. Sintering leads to reduction of void volume and reinforcement of continuous bridge which is shown in Figure 2. Sintering is responsible for strengthening of fouling layer and it is start below the melting point of fouling layer material. The stages of particulate fouling are illustrated in Figure 3, as stated by Abd-Elhady *et al*. as fouling layer increases, there is increase in thermal resistance (Abd-Elhady *et al*., 2005).

Figure 2. Fouling in EGR cooler (Abd-elhady *et al.*, 2011)

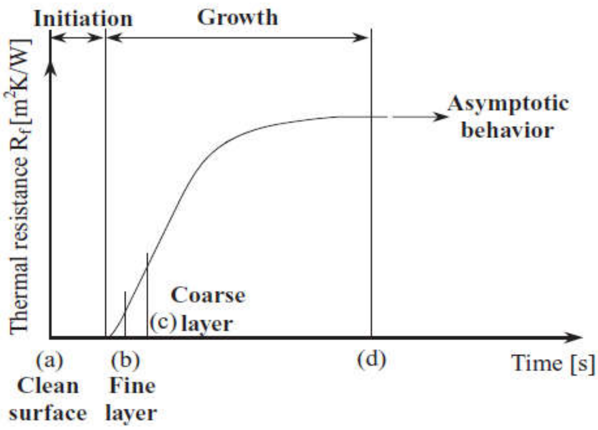

Figure 3. Stages of particulate fouling (Abd-Elhady *et al.*, 2005)

Adverse effect of fouling

- Decrease in thermal efficiency and increase in pressure drop
- Engine efficiency and EGR cooler effectiveness decreases
- Reduces heat transfer coefficient and increases formation of NOx

Techniques to lower fouling

Gas velocity: for reduction of fouling gas velocity must be increases such that gas velocity is greater than critical velocity of flow. Due to increase in gas velocity incident particles impact on fouling layer and drag particulate matters outside the tubes.

Catalyst addition: The use of oxidation catalyst is to oxidized unburned hydrocarbon such as diesel oxidation catalyst (DOC). These unburned hydrocarbons are trapped in diesel particulate filter (DPF). These trapped particles oxidized by DOC and after that exhaust gas provided to EGR cooler so that fouling problem is reduced. The effect of addition of catalyst on effectiveness of EGR cooler system with time is shown in Figure 4.

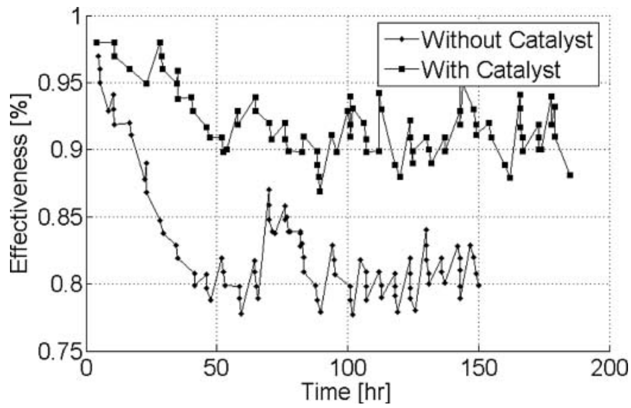

Figure 4. EGR cooler system effectiveness V/S engine running hours, with and without an EGR catalyst (Abd-elhady *et al.*, 2011)

Mechanical stresses: When a material is loaded with a force, it produces a stress, which then causes a material to deform. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material. This type of failure depends on vibrations, material used and dimensions of component.

Vibrational failure: Every component of system vibrates with their natural frequency. During running condition of vehicle components of EGR cooler excited depending upon the road condition. When the natural frequency of components matches with excited frequency of system it causes resonance and system vibrates at very large frequency which is not desirable. Thus, resonance of system can lead to failure of components.

Structural failure: Structural integrity is the ability of an item either a structural component or a structure consisting of many components to hold together under a load, including its own weight, without breaking or deforming excessively. Structural failure refers to the loss of structural integrity, or the loss of load -carrying capacity in either a structural component, or the structure itself.

Structural failure can occur from many types of problems such as (https://en.wikipedia.org/wiki/Tem pering_ (metallur gy))

- The structure is not strong and tough enough to support the load, due to its size, shape, or choice of material.
- Failure is due to fatigue or corrosion, caused by instability in the structure's geometry, design or material properties.
- Failure is caused by manufacturing errors, including improper selection of materials, incorrect sizing, improper heat treating, failing to adhere to the design, or shoddy workmanship.
- Failure is due to the use of defective materials.

Salunkhe *et al*. (Pravin S. Salunkhe and Dhummansure, S. R. Babar, 2015) studied the failure of EGR housing due to its loading conditions. The loading setup of EGR housing is shown in Figure 5. The material of Housing, Brackets and Bolts are as shown in Table 1. By applying appropriate mounting condition, FEA on EGR housing was performed. From FEA it is found that at bosses stress developed was beyond permissible limit which causes failure of bosses. By analysis it is found that maximum deflection occurs at about 0.63mm and maximum stress about 283 MPa which is shown in Figure 6. To reduce the failure Salunkhe *et al*. (Pravin S. Salunkhe and Dhummansure, S. R. Babar, 2015) increases the thickness and introduced rib to support bosses. Due to this structural rigidity and strength improved up to 80% and displacement was reduced by 6 times.

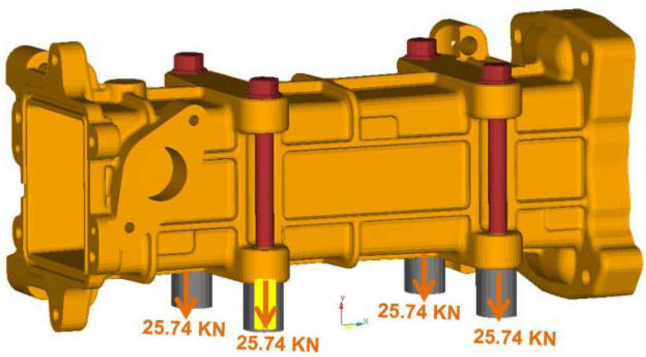

Figure 5. Loads on housing (Pravin S. Salunkhe and Dhummansure, S. R. Babar, 2015)

Table 1. Mechanical materialproperties (Pravin S. Salunkhe and Dhummansure, S. R. Babar, 2015)

Material	Aluminium	Cast Iron	Steel
Parts	Housing	Brackets	Bolt
Young's Modulus E (MPa)	6.8 E4	1.69 E5	2.1 E5
Poisson's ratio μ (-)	0.33	0.3	0.30
Mass Density ϱ (ton/mm^3)	2.7 E-9	7.1 E-9	7.8 E-9
Thermal Exp. Co. α (mm/K)	2.4 E-5	2.4 E-5	2.1 E-5

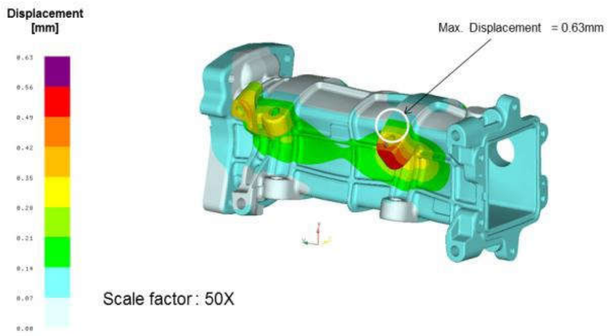

Figure 6. Deflections in Housing (Pravin S. Salunkhe and Dhummansure, S. R. Babar, 2015))

Corrosion

The exhaust gases emitted from the vehicle are nitrogen oxides (NO_x), carbon dioxide (CO_2), hydrocarbons (HC), and particulate matter (PM). These exhaust gases react with atmospheric air to form respective acid, such as sulphuric acid, hydrochloric acid, etc. the acid form from exhaust gases collected on metal surface and corrosion of metal start.

Formation of Sulphuric Acid

During combustion process most of the sulphur is converted into gaseous SO_2. This gaseous SO_2 react with oxygen in exhaust to form SO_3.

$$2SO_2 + O_2 \rightarrow 2SO_3$$

The SO_3 further reacts with moisture in the exhaust to form sulphuric acid according to following reaction (Michael D. Kass *et al*., 2004)

$$2SO_3 + H_2O \rightarrow H_2SO_4$$

$$2SO_2 + O_2 + 2H_2O \rightarrow 2\ H_2SO_4 \text{(Net Reaction)}$$

Under typical exhaust conditions sulfuric acid will condense near temperatures approaching 150˚C while water condensation will occur at temperatures close to 25-30˚C. Michael *et al*.(2004) discussed the corrosivity associate with exhaust gas recirculation system for that purpose author did one experiment on diesel engine using two types of fuel; an ultra-low sulphur bearing fuel containing less than 15 ppm and standard No. 2 diesel fuel containing approximately 350 ppm sulfur. The engine was run at speeds between 1200 and 1550 rpm and torque ranging from 454 to 542 Nm (80-90% of full load). The exhaust pressure was high enough to overcome boost pressure. During experiment EGR level was from 5 to 16% depending on conditions. A standard analytical bench was used to measure exhaust gases. The conditioned combustion air handling system maintained the humidity and dew point temperature. The corrosion probe take minimum 30 min to indicate exhaust gas corrosion therefore, corrosion monitoring time is set to 45 min. During this test the supply air humidity and temperature were maintained at 56 % and 24˚C, respectively. The results obtained from corrosion probe with ultra-low sulphur (15 ppm) fuel are shown in Figure 7. For condensing and non-condensing conditions the corrosion rate was obtained below 1 mm/year. Therefore for this fuel the EGR fraction does not have observable effect on corrosion rate. The corrosion rate for the fuel containing 350 ppm sulphur was shown in Figure 8. For this fuel there was no non condensing condition. This condition is significant because condensation for sulfuric acid can be expected to occur near temperatures approaching 150˚C for combustion exhaust systems. The corrosion rate for 350 ppm sulphur fuel was quit greater than 15 ppm sulphur fuel. These results indicate the probable corrosion of diesel engine due to 350 ppm S fuel. As 350 ppm S fuel shows significant corrosion rate therefore it was examined for humidity. The relative humidity was controlled by using the air handling unit in the range between 53 to 58%. The result appears for corrosion rate with humidity while operating the engine using 350 ppm S fuel as shown in Figure 9. The data obtained do not show any correlation of rate of corrosion with humidity.

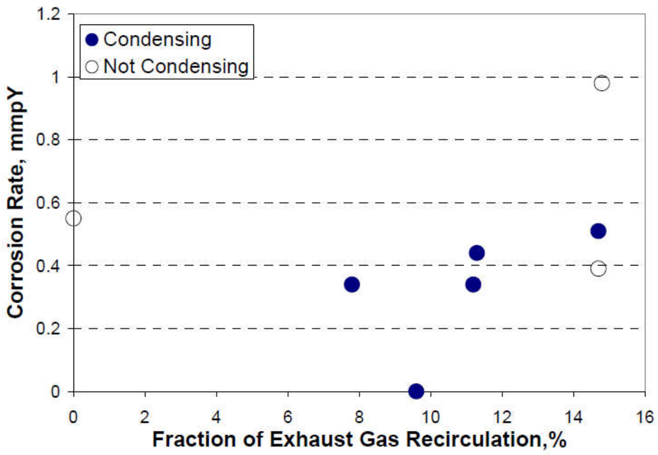

Figure 7. Corrosion rate as a function of EGR fraction and condensation for low sulphur (15 ppm) fuel (Michael D. Kass *et al.*, 2004)

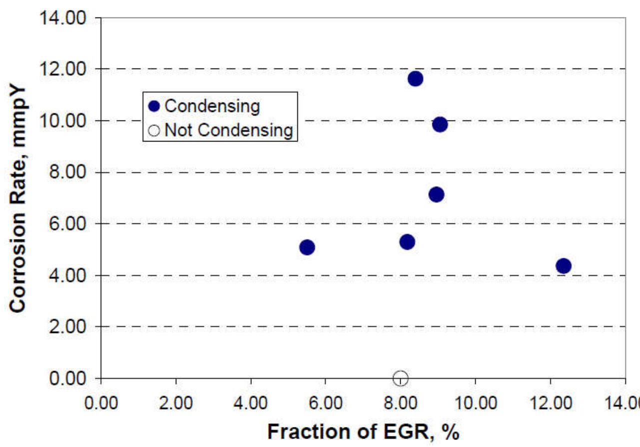

Figure 8. Corrosion rate as a function of EGR fraction and condensation for high sulphur (350ppm) fuel (Michael D. Kass *et al.*, 2004)

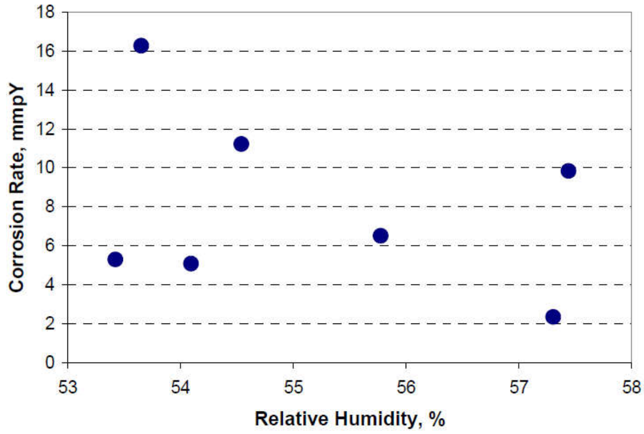

Figure 9. Corrosion rates as a function of humidity while operating using 350 ppm sulphur fuel and undergoing condensation (Michael D. Kass *et al.*, 2004)

Boiling

Boiling is the rapid vaporization of a liquid, which occurs when a liquid is heated to its boiling point, the temperature at which the vapour pressure of the liquid is equal to the pressure exerted on the liquid by the surrounding atmosphere. Higher the pressure higher the boiling point. There are two main types of boiling; nucleate boiling where small bubbles of vapour form at discrete points, and critical heat flux boiling where the boiling surface is heated above a certain critical temperature and a film of vapor forms on the surface. Transition boiling is an intermediate, unstable form of boiling. Boiling inside the EGR cooler is forced convection boiling as shown in Figure 10. Nucleate boiling increases the heat transfer coefficient and Film boiling decreases the heat transfer coefficient. Running the cooler under boiling conditions and cyclic thermal load will result in cooler failure.

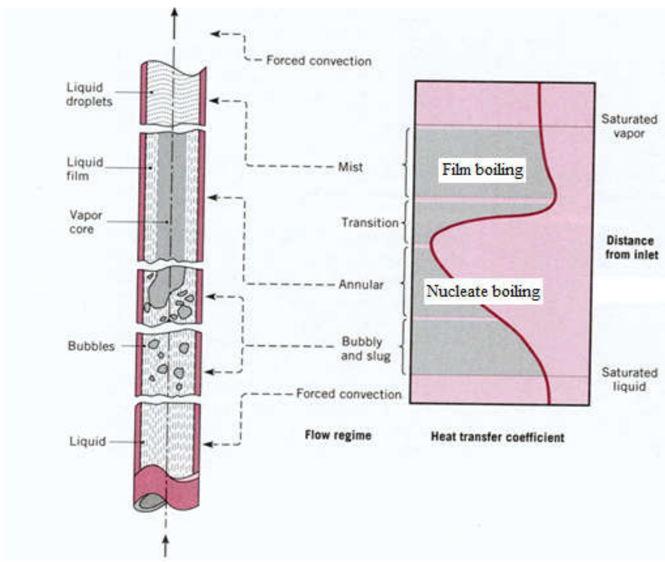

Figure 10. Boiling in forced convection (Julio Carrera, 2016)

Boiling detection

- Boiling is detected by using annealing colors on the tubes (Refer Figure 11)
- The absence of annealing colors does not prove, that there was no boiling
- Boiling is possible without annealing colors
- No boiling is allowed in case of EGR cooler

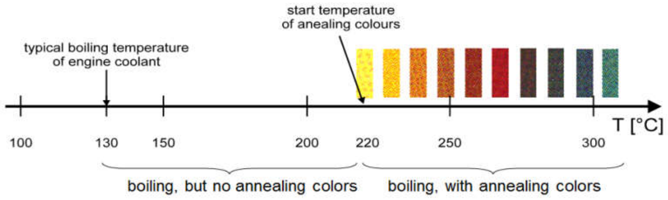

Figure 11. Annealing colors of steel (https://en.wikipedia.org/wiki/Tempering_(metallurgy))

Technique to lower boiling in EGR cooler

Addition of glycol in coolant has several influences

- Glycol increases the boiling temperature therefore boiling risk is reduced
- Glycol work as a corrosion inhibitor
- Avoid deposition on tubes

Thermal Stresses

Thermal stress is stress created by any change in temperature to a material. These stresses can lead to fracture or plastic deformation depending on the other variables of heating, which include material types and constraints. Temperature gradients, thermal expansion or contraction and thermal shocks are things that can lead to thermal stress. This type of stress is highly dependent on the thermal expansion coefficient which varies from material to material. In general the larger the temperature change, the higher the level of stress that can occur. When a material is rapidly heated or cooled, the surface and internal temperature will have a temperature difference. Quick heating or cooling causes localized areas of thermal expansion or contraction; this localized movement of material causes thermal stresses (Dalei Li *et al*., 2012). The thermal crack in exhaust header is shown in Figure 12.

Figure 12. Thermal cracks in exhaust header (https://www.centuryperformance.com/exhaust-header-heat-wraps-do-not-use.html)

Conclusion

From the study of failure modes of EGR cooler following conclusions are made

- Fouling of cooling coils is one of the predominant factor of EGR system failure which is reduced by using oxidation catalyst such as Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF).
- The failure of EGR housing, brackets and bellow pipe is due to mechanical stresses. For elimination of these type failure, material checking or redesigning of component for desired work condition is required.
- Corrosion of system is mainly affected by amount of sulphur in engine fuel and condition of relative humidity of supply air.
- Boiling is detected by using annealing color. There is no boiling is allowed for EGR cooler. Boiling in EGR cooler is reduced by adding proper amount of glycol in coolant.
- Thermal stresses in EGR system are highly dependent on its thermal expansion coefficient. Thermal stresses leads to cracking of components.

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