

An Empirical Methodology for the Prediction of the Boiling Limits of EGR Coolers

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ABSTRACT

Recent emissions standards have become more restrictive in terms of CO₂ and NO_x reduction. This has been translated into higher EGR rates at higher exhaust gas temperatures with lower coolant flow rates for much longer lifetimes. In consequence, thermal load for EGR coolers has been increasing and the interaction of boiling with thermal fatigue is now a critical issue during development.

It is almost impossible to avoid localized boiling inside an EGR cooler and, in fact, it would not be strictly necessary when it is below the Critical Heat Flux (CHF). However when CHF is exceeded, film boiling occurs leading to the sudden drop of the heat transfer rate and metal temperature rise. In consequence, thermal stress increases even when film boiling is reached only in a small area inside the part. It is very difficult to accurately predict under which conditions CHF is reached and to establish the margins to avoid it. In this work, a new empirical method has been developed that covers an innovative prototype instrumentation with thermocouples that allows the direct measurement of the metal temperature in any location inside the prototype; the boiling test methodology and the postprocess to check when CHF is reached.

An analytical correlation of a boiling parameter called Cooler Boiling Ratio enables the prediction of safety margin against CHF for any working condition. Several tests were performed to check the robustness of the method with successful results so this research represents an important progress in the empirical approach for boiling analysis in EGR coolers.

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INTRODUCTION

EGR works by recirculating a portion of engine's exhaust gas back to the engine cylinders. The EGR systems main components are shown in Fig.1.



Figure 1. EGR system components.

Boiling is the rapid vaporization of a liquid, which occurs when a liquid is heated to its boiling point. It occurs in three characteristic stages, which are nucleate, transition and film boiling. Boiling itself is not an issue, and some authors recommend it because the use of boiling in engine cooling systems offers higher heat transfer. The drawback is that if part boiling appears, wall temperature increase drastically and the part fails very quickly. This happens when CHF point is reached (Fig. 2).

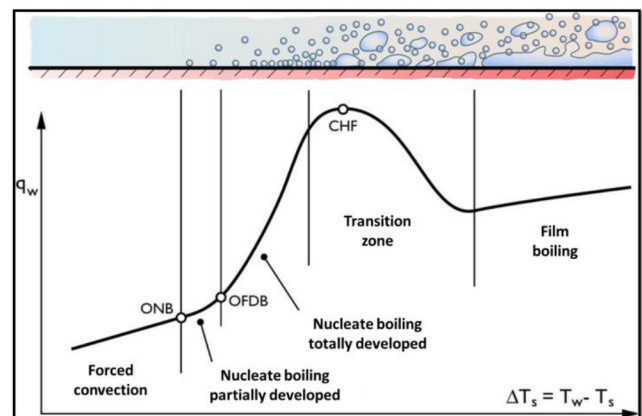


Figure 2. Boiling curve.

In consequence boiling affects thermal fatigue in two ways:

1. Below CHF nucleate boiling occurs, heat transfer is enhanced and metal temperature is limited.
2. When film boiling occurs, stresses in the part increase drastically causing an early failure.

Previous investigations [1] have shown clear interaction between boiling and thermal fatigue in EGR coolers. Due to thermal stresses in the components, which depend mainly on temperature field, durability drops drastically when metal temperature increases due to film boiling. Besides, heavy boiling makes almost impossible to perform accurate Thermo-mechanical analyses (TMA) or any other analytical estimation, so it is very important to avoid it.

Figure 3 shows the effects on the inner tubes of an EGR cooler when CHF is exceeded, metal shows deep temper color marks due to high temperature and coolant silicate depositions appear when film boiling occurs. Durability in these cases is very low so these boiling issues must be avoided.

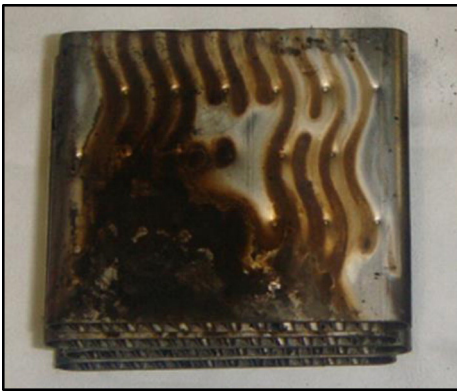


Figure 3. Film boiling marks in inner tube.

In this work a new empirical methodology is developed which means an important step forward in terms of CHF detection and boiling risk quantification for EGR coolers.

BOILING TEST

Boiling test is one of the most important tests during EGR cooler development. Historically this kind of test has been based on visual inspection in the outlet port of the part because the engine coolant circuit cannot support a high level of bubbles. Coolant pump can be damaged and bubbles could be accumulated in the engine cooling jacket causing local overheating, coolant fluid degradation or even excessive silicates deposition.

Figure 4 shows the typical layout of a boiling test. Gas and coolant circuits are connected to the test bench and a transparent window is located in the coolant outlet port in order to see the amount of bubbles that come out. In some cases transparent windows can also be placed in the outer shell of the test sample for allowing visual inspection of boiling level inside the part.

In these tests the gas and coolant circuits of the components must have the same set-up and configuration as the engine or vehicle and the EGR cooler position and orientation must be the same. The reason is that boiling depends strongly on gravity, ports location and coolant stream.

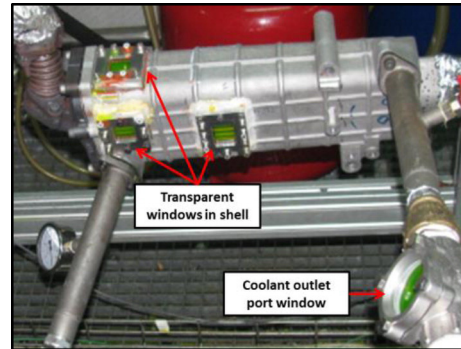


Figure 4. Boiling test layout.

Other test measurements that can be very helpful for understanding the boiling behavior of an EGR cooler are thermographic recordings and temperature measurements in the outer shell in order to check if bubble accumulation occurs, which can be detected when hot spots appear in the upper side of the shell as figure 5 shows.

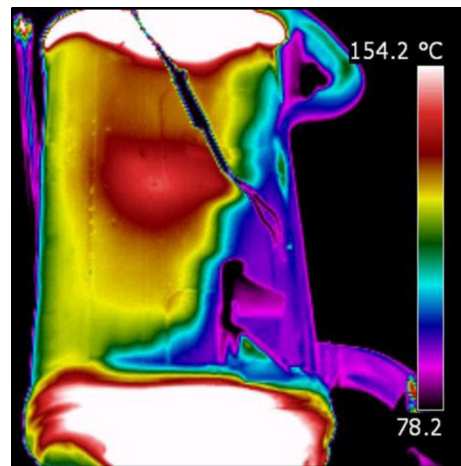


Figure 5. Thermographic picture of EGR cooler under heavy boiling conditions.

This kind of test normally consists of fixing the working parameters, except coolant flow, which is reduced in order to see what the effect in boiling level is. These tests have been performed in recent years providing very important information for project development. The drawback of this kind of tests is that they provide limited information:

- Measurement of bubble quantity is very complex, visual inspection gives a qualitative idea of the boiling severity.
- Sometimes boiling level in the outlet of the test sample is low but boiling level inside the part is very high. This occurs in those cases where degasing is deficient and bubbles cannot come out, this is the worst situation possible for the robustness of the part.
- Thermographic recordings and temperature measurements in the outlet shell are useful when bubble accumulation occurs in the upper side of the shell, but they are not suitable for checking bubbles accumulation among the inner tubes.

EGR cooler instrumentation

Due to the boiling test based on visual inspection or outer shell temperature measurements has several limitations, an innovative instrumentation procedure for EGR coolers with thermocouples was developed.

A thermocouple is a device consisting of two dissimilar conductors or semiconductors that contact each other at one or more points. A thermocouple produces a voltage when the temperature of one of the contact points differs from the temperature of another, in a process known as the thermoelectric effect. Thermocouples are a widely used type of temperature sensor for measurement and control. The most common general purpose thermocouples is the Type K (chromelalumel). A wide variety of probes are available in the range of -200°C to $+1350^{\circ}\text{C}$. In this work type-K thermocouples were selected due to high temperature resistance properties.



Figure 6. Thermocouple schema.

The new instrumentation process consists of building the test prototypes with the temperature sensor embedded inside the inner core among the tubes. EGR coolers produced by BorgWarner are brazed in a furnace so taking advantage of brazing process the thermocouples are brazed together with the prototype, this has several advantages:

- Sensors can be located in any area inside the EGR cooler, no matter how difficult the access is, because the sensors are installed during the prototype assembly process.
- Because the sensors are brazed directly to the metal, contact is perfect and temperature measurement is very reliable.
- Fixation is also perfect and the robustness of this kind of instrumentation is very good, allowing to test under heavy thermal conditions for a long period of time. Parts can be tested in clean conditions on the test bench, then be sent for acquisitions in dyno test bench or vehicle tests and finally be tested once again on the test bench with no issues. This provides a lot of information and very good comparison between engine/vehicle and test bench.

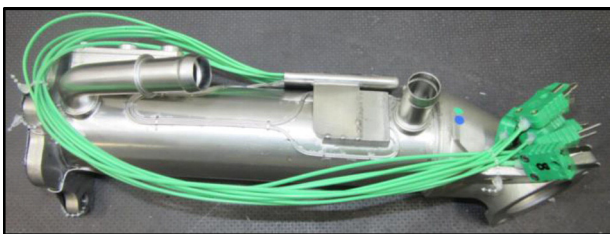


Figure 7. Prototype instrumented with thermocouples.

Sensor location inside the part is based on a previous computational fluid dynamics calculation (CFD) in order to check which are the areas with the highest temperatures (figure 8 and 10). In an EGR

cooler normally the areas more susceptible to have film boiling are located near the hot header, so although the thermocouples are located in several zones inside the cooler, the instrumentation is focused around the hot header.

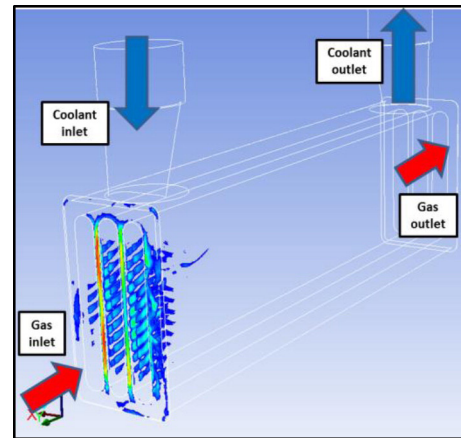


Figure 8. Example of areas with higher heat transfer in an EGR cooler.

Test procedure

The objective of the new boiling test developed in this work is not only to check the amount of bubbles in the coolant outlet port, or to check which are the temperatures of the skin metal temperature inside the part, but also to find out in which conditions CHF is reached and characterize the behavior of the part against boiling under any possible working condition.

This means that it is not sufficient to only change coolant flow for a given test point, it is necessary to make sweeps with every test parameter involved: gas mass flow, coolant flow, gas inlet temperature, coolant inlet temperature and coolant inlet pressure. Sweeps must be done also at different working conditions in order to capture the influence of every parameter over the rest.

Every sweep must start in a low boiling condition and then the parameter is modified in the direction of increasing boiling level until reaching the maximum level possible for the test bench or very high temperatures inside the cooler. The objective is to test points with no boiling or low boiling level, and also points with film boiling. Table 1 shows an example of a test matrix, where:

mg = gas mass flow

Tg = inlet gas temperature

mc = coolant flow

Tc = inlet coolant temperature

Pc = inlet coolant pressure