

Modeling Approach to Estimate EGR Cooler Thermal Fatigue Life

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ABSTRACT

Cooled EGR continues to be a key technology to meet emission regulations, with EGR coolers performing a critical role in the EGR system. Designing EGR coolers that reliably manage thermal loads is a challenge with thermal fatigue being a top concern. The ability to estimate EGR cooler thermal fatigue life early in the product design and validation cycle allows for robust designs that meet engine component reliability requirements and customer expectations. This paper describes a process to create an EGR cooler thermal fatigue life model. Components which make up the EGR cooler have differing thermal responses, consequently conjugate transient CFD must be used to accurately model metal temperatures during heating and cooling cycles. Those metal temperatures are then imported into FEA software for structural analysis. Results from both the CFD and FEA are then used in a simplified numerical model to estimate the virtual strain of the EGR cooler. Using the virtual strain output, Rainflow cycle counting, Palmgren-Miner linear damage accumulation, along with a detailed understanding of customer duty cycles the EGR cooler thermal fatigue life is estimated. Model validation was completed by accurately estimating the number of thermal cycles to failure during component rig bench tests and on multiple customer field units.

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INTRODUCTION

Since 2002, heavy duty diesel engines have utilized cooled exhaust gas recirculation (EGR) to support meeting United States federal nitrogen oxide emission limits with a key component being the EGR cooler. EGR coolers are primarily shell and tube type heat exchangers made of stainless steel. Under certain engine operating conditions, wall temperatures of the EGR cooler are low enough for acidic condensation to form [1], therefore, stainless steel is used to prevent corrosion from acids. Typical EGR cooler construction utilizes a central shell with other components welded to it such as header plates, gas diffuser and collector, coolant inlet and outlets. Tubes (with or without internal fins) are either welded or brazed to a header plate which is then welded to the shell. Tube designs can be placed into one of three design categories-tube and fin, winglet tube, and corrugated tube. This paper will focus on a corrugated tube EGR cooler design but the modeling and life prediction techniques can be adapted to other designs. With EGR cooler gas inlet temperatures in excess of 650°C and the cyclic nature of EGR flow based on the duty cycle, thermal fatigue at the gas inlet header is a concern. A typical thermal fatigue crack is shown in Figure 1 and initiates on the inside diameter of a given tube and propagates through the header plate to another tube. An EGR cooler thermal fatigue failure allows coolant to enter the exhaust stream with the customer noticing coolant loss over time. This not only drives customer down-time to replace the EGR cooler but can also cause progressive damage to the turbocharger and exhaust aftertreatment devices. Therefore, being able to evaluate a given designs robustness to thermal fatigue early in the engine development cycle is a key advantage.

Using computational fluid dynamics (CFD) and finite element analysis (FEA) procedures to evaluate EGR cooler designs for thermal fatigue with a limited set of boundary conditions is documented [2] [3]. Procedures that can quickly analyze large data sets from customer field test units, engine durability tests, and component thermal fatigue rigs are not nearly as developed. For this reason, a simplified numerical model was developed to estimate EGR cooler thermal fatigue life. Figure 2 describes the process flow for creating a model to estimate EGR cooler thermal fatigue life and also outlines the body of this paper. The final section of the paper describes the model validation by comparing the estimated fatigue life to thermal cycle rig and customer field failures.

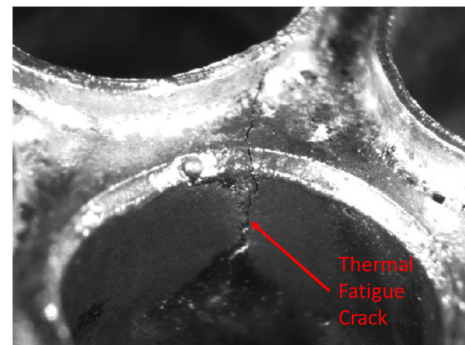


Figure 1. Typical thermal fatigue crack.

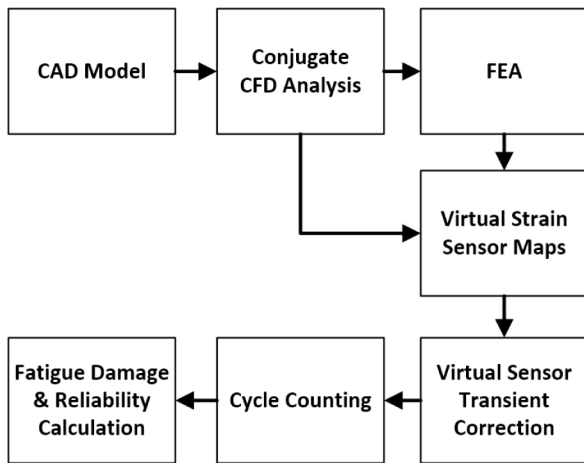


Figure 2. EGR thermal fatigue life model process flow.

CAD MODEL

The EGR cooler examined in this paper is a production 2007 ISX 15L engine cooler design. The cooler is a tube and shell design that utilizes 104 corrugated tubes brazed to the header which is then welded to the shell and diffuser. The CAD model used was as close to the actual part geometry as practical with minimal simplified geometry. The corrugated tubes are simplified to straight tubes with an orifice sized for overall gas side pressure drop and flow distribution. The length of the EGR cooler was shortened since the differential thermal expansion of the corrugated tubes was found to cause insignificant strain at the header. This assumption is for modeling convenience only, it is not a requirement of the modeling methodology described in the remainder of this paper. Joint welds of the cooler are modeled since they add thermal mass and stiffness. Figure 3 shows the geometry of the EGR cooler analyzed.

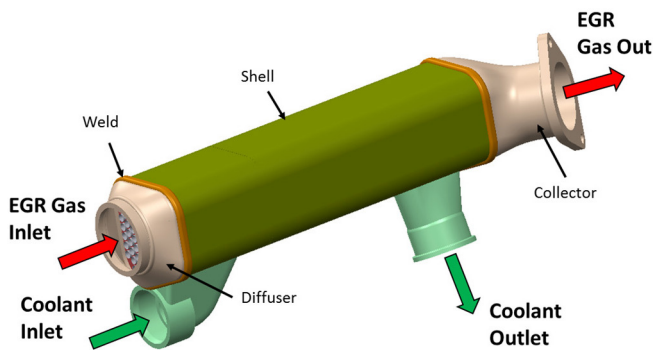


Figure 3. EGR cooler external part layout.

CONJUGATE CFD ANALYSIS

Steady-state and transient conjugate CFD analysis was completed using STAR-CCM+. Conjugate CFD is required to accurately model metal temperature based on coolant and gas side boundary conditions. Ambient air conditions were accounted for with a constant heat transfer coefficient and temperature applied to all external surfaces. Assumptions for CFD analysis are as follows:

1. Coolant and solid material properties are assumed to be constant over the working range of temperatures.

2. Coolant boiling is not considered.
3. Radiation is not considered.

The CFD analysis is broken up into two cases—steady-state and transient. For each case there are three domains: gas, coolant, and solid. A polyhedral mesh was used to lower the total cell count and subsequently reduce the total analysis run time. Mesh base size of 6.0 mm with a growth rate of 1.3 was used and resulted with 4.8 million total cells. Mesh details for a cross section of the EGR cooler is shown in Figure 4.

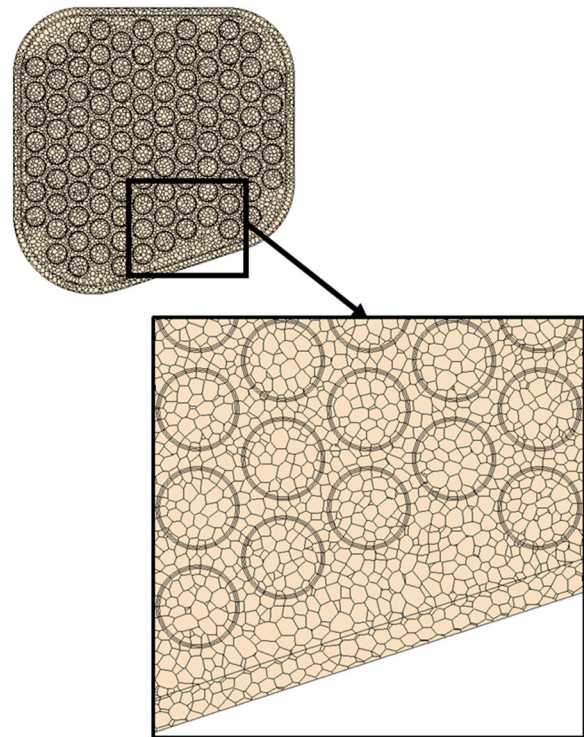


Figure 4. Polyhedral mesh details.

A matrix of 136 steady-state analysis boundary condition points was chosen based on the engine operating space. Constant coolant side boundary conditions were kept while EGR gas temperature and mass flow rate were varied. The need for this matrix of conditions will be described in subsequent sections. Figure 5 shows temperature points selected on the diffuser and header. The diffuser point was chosen arbitrarily, however, the header point is close to the typical crack location and these locations will change based on the EGR cooler design. Results from these two points are output for each boundary condition and are shown in Figure 6a and 6b with the gray dots representing the analysis boundary conditions. For each analysis point the nodal metal temperatures were exported for structural analysis.

Transient analysis was completed to investigate the thermal response of individual components that make up the cooler and to understand transient strain effects during heating and cooling conditions.

Boundary conditions are shown in Table 1. They were chosen based on the engine operating space, and they represent moving from low idle to a powered condition. Transient analysis started from steady-state low idle conditions, then a step input change to the powered conditions until steady-state was reached, and finally a step input

back to low idle conditions until steady-state. The diffuser and header temperature response is shown in Figure 7. It can be seen that the header was heating and cooling at a much faster rate than the diffuser. Nodal metal temperatures were exported at 1 second intervals for structural analysis.

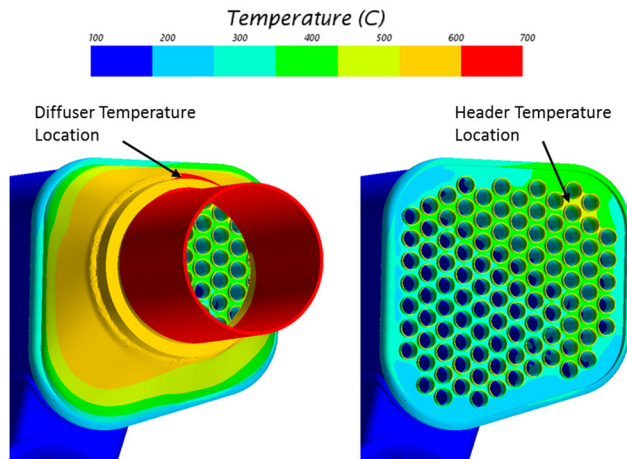


Figure 5. Diffuser and header temperature reporting point locations.

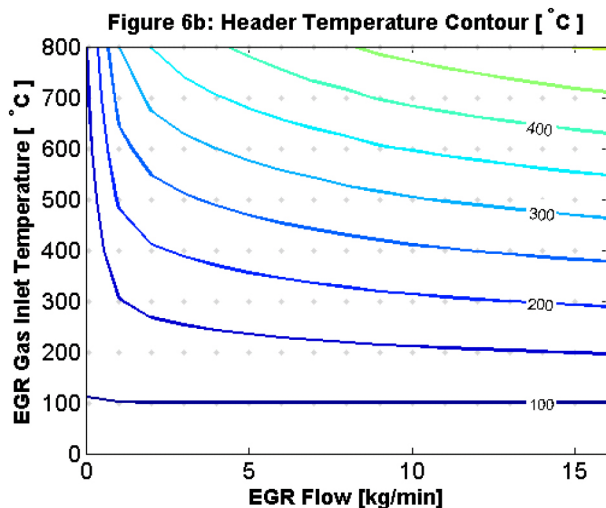
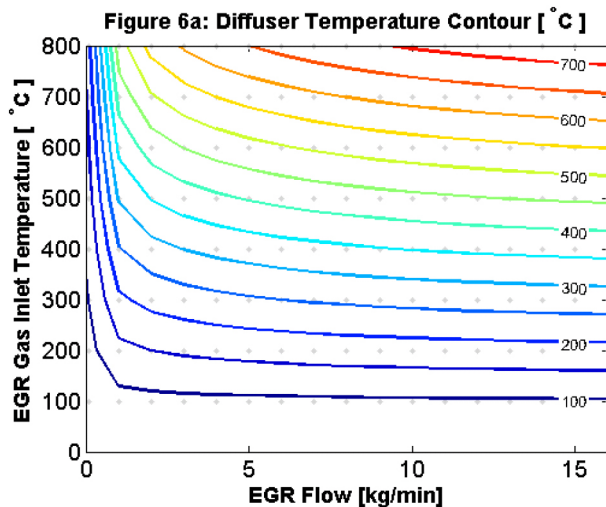


Figure 6a and 6b. Steady-state diffuser and header temperature contour plots.

Table 1. Transient CFD boundary conditions

Parameter	Heating	Cooling
EGR Flow [kg/min]	15	2.5
EGR Inlet Temperature [K]	948	533
EGR Outlet Pressure [kPa-g]	400	120
Coolant Flow [L/sec]	4.3	1.9
Coolant Outlet Pressure [kPa-g]	230	112
Coolant Inlet Temperature [K]	363	363
Ambient Temperature [K]	313	313
Ambient HTC [W/m ² -K]	25	25

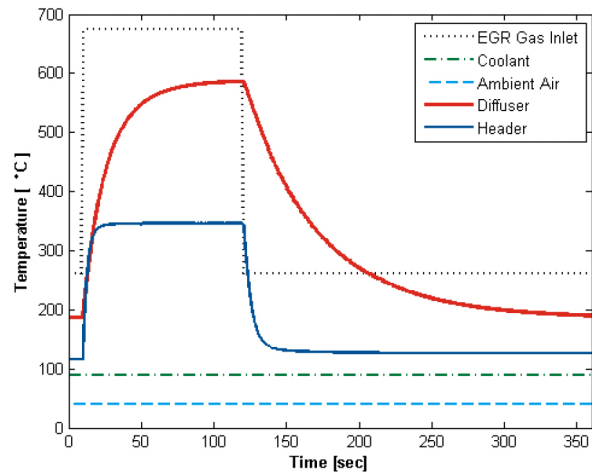


Figure 7. Transient diffuser and header temperature response.

FINITE ELEMENT ANALYSIS

Structural analysis was completed using ANSYS Workbench. Nodal temperature files from CFD analysis were imported into ANSYS Workbench and mapped onto model surfaces for structural analysis.

Assumptions for structural analysis were as follows:

1. It was assumed that the mechanical time constant is much faster than the thermal time constant. That is to say, the transient response in stress and strain is determined by the transient response in temperature.
2. It was assumed to operate in the linear elastic material regime.
3. Only the front quarter portion of the EGR Cooler was considered.

Assumption 3 is based on the EGR cooler using corrugated tubes; therefore, when under hot conditions, the mismatch in thermal expansion won't generate significant axial loading. Nonlinearities in the materials are accounted for with the fatigue life analysis rather than non-linear materials in the structural analysis.

Fixed support was applied to the cut portion of the shell, and in order to report the normal stress a cylindrical coordinate system was applied to the tube near crack initiation. Figure 8 shows a cross section of the model used for structural analysis.