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EGR Cooler Fouling Reduction: A New Method for Assessment in Early Engine Development Phase

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Abstract

High pressure EGR provides NO_x emission reduction even at low exhaust temperatures. To maintain a safe EGR system operation over a required lifetime, the EGR cooler fouling must not exceed an allowable level, even if the engine is operated under worst-case conditions.

A reliable fouling simulation model represents a valuable tool in the engine development process, which validates operating and calibration strategies regarding fouling tendency, helping to avoid fouling issues in a late development phase close to series production.

Long-chained hydrocarbons in the exhaust gas essentially impact the fouling layer formation. Therefore, a simulation model requires reliable input data especially regarding mass flow of long-chained hydrocarbons transported into the cooler.

There is a huge number of different hydrocarbon species in the exhaust gas, but their individual concentration typically is very low, close to the detection limit of standard in-situ measurement equipment like GC-MS.

Therefore, a new measurement and analysis approach has been developed, where the exhaust gas is guided to a metal foam collector, in which HC`s are deposited. The probe is then analyzed in a suited thermogravimetrical system (TGA) in nitrogen atmosphere, temperature range 25°C to 650°C. Analyzing the TGA curve, HC concentration data for 6 different boiling temperature ranges are obtained, provided to an adapted 1-d fouling simulation model.

Using these data along with further input parameters like cooler geometry, gas temperature, pressure, flow, particle size distribution and coolant temperature, the simulation model has proven as a suitable tool to predict the fouling and identify engine settings for fouling reduction.

Introduction

Cooled EGR represents a well-established technology for NO_x emission reduction. It even works at exhaust temperatures too low for proper operation of SCR systems, e.g. in the engine warmup phase or during long idle phases under cold ambient conditions. One key challenge to the system is the fouling of components like EGR valve, pipes, bypass flaps and in particular the EGR cooler. Figure 1 shows as an example the outlet side of an EGR cooler after durability test.

Fouling effects significantly reduce the EGR cooler efficiency, resulting in cooling power loss. So, gas temperature downstream the cooler can even exceed allowable limits. Additionally, the increased flow resistance may require higher difference pressure over the cooler in order to maintain a demanded EGR-flow, leading to a decrease of gas exchange efficiency. In the worst case, demanded EGR rates cannot be achieved anymore, or EGR valves get stick. Even the detection of such malfunction might require a special diagnostics strategy [1].

To avoid this over a required engine lifetime, it is necessary to find an engine operation strategy and calibration, which keeps the EGR cooler fouling below an allowable limit.

Endurance test based fouling validation typically takes place in a late engine development phase. If there a severe fouling issue is recognized, countermeasures in engine operation strategy and calibration are challenging to be realized. Thus, a valid fouling simulation model, covering the impact of real exhaust gas composition, is a valuable tool in the engine development process, providing a rapid fouling assessment in an earlier development phase.

This paper describes a new approach on how the concentration of fouling-relevant hydrocarbons in the EGR path can be estimated. Further, it is shown how these results can be applied to a 1-d fouling simulation model. A result example shows the usefulness of such a model for the validation of fouling reduction measures.

All simulation and test work presented in this paper has been carried out for Diesel engines with high-pressure EGR system, EGR cooler position downstream EGR valve.

It has to be concluded, that a soot reduction measure not necessarily leads to reduced fouling, it even can get worse, if more fouling-relevant HC are emitted.

Different engine calibration, in the example incorporated by a setting of reduced rail pressure, retarded injection and reduced EGR rate, can lead to clearly reduced concentration of fouling-relevant HC. In consequence, the deposited HC mass is decreased by ~60% compared to basis calibration. Along with reduced soot concentration, a total deposit mass reduction of about 70% can be achieved.

Comparing the parameter variation results for both engines, no clear pattern can be recognized regarding the mechanisms of fouling-relevant HC generation. In fact, further research work is recommended to gain understanding on all impacting parameters.

Simulation Model Validation

The fouling simulation model presented has been validated using various engine endurance test results. The engines were operated on test rigs in low load cycles, representing short track vehicle operation, which typically forces EGR cooler fouling, for an entire engine lifetime, typically more than 1500 hours. During endurance test inspections, the EGR cooler weight was recorded, indicating a cooler mass increase due to fouling.

During the cooler run-in phase, a forced mass increase has been observed for all tests, which is in accordance with the findings of Abd-Elhady and Malayeri [25]. They conclude that this effect is mainly caused by the low surface temperature in the cooler, if no thermal insulating soot layer covers it. With increasing deposit layer thickness over time, the higher surface temperature leads to reduced thermophoretic effect.

When excluding the cooler run-in phase, a rather constant fouling rate can be recognized for a long period. A typical value for a passenger car engine is 3g per 100 hours low load endurance test.

For simulation model validation, the endurance test profile, i.e. engine speed and load vs. time, was stipulated to the model, and this way the endurance test was simulated for the entire operation time. This war the fouling evolution as well as the fouling rates in the nearly constant fouling range can be compared. Figure 10 displays the simulated and measured fouling rate results for 3 different passenger car engines in the same test regime. Even if the exhaust composition varies, the impact is reflected well by the model. For the EU6 Variants, the Model calculates 5% and 3% higher fouling rate for Setup A and Setup B respectively. The EU5 Variant is 6% underestimated. Overall, a good alignment of simulation results with measurement results can be stated.

Summary/Conclusions

To support the engine development process with reliable EGR cooler fouling simulation, the composition of real exhaust gas including fouling-relevant HC needs to be input to the model.

A new method has been presented, using a sample collector made of metal foam, analyzing it with TGA and applying the resulting concentration values to representative HC species as input data to the 1-d model. Based on that procedure it is possible to distinguish between different calibration settings regarding their fouling impact, which can be very helpful in an earlier development phase.

Simulation results of an endurance test show good alignment with measured results from test rig.

Further research work is recommended to identify mechanisms that lead to formation and emission of long-chained hydrocarbons.

References

1. Dadam, S.R., Jentz, R., lenzen, T., and Meissner, H., "Diagnostic Evaluation of Exhaust Gas Recirculation (EGR) System on Gasoline Electric Hybrid Vehicle," SAE Technical Paper 2020-01-0902 (2020). https://doi.org/10.4271/2020-01-0902.
2. Paz, C., Suárez, E., Vence, J., and Cabarcos, A., "Numerical Modelling of Fouling Process in EGR System: A Review," *IntechOpen Environmental Issues and Sustainable Development*, doi:10.5772/intechopen.93062.
3. Warey, A., Balestrino, S., Szymkowicz, P., and Malayeri, M.R., "A One-Dimensional Model for Particulate Deposition and Hydrocarbon Condensation in Exhaust Gas Recirculation Coolers," *Aerosol Science and Technology* 46, no. 2: 198-213, doi:10.1080/02786826.2011.617400.
4. Abarham, M., Hoard, J., Assanis, D., Styles, D. et al., "Review of Soot Deposition and Removal Mechanisms in EGR Coolers," *SAE Int. J. Fuels Lubr.* 3, no. 1 (2010): 690-704. https://doi.org/10.4271/2010-01-1211.
5. Hörnig, G., "Analysis of Aerosol Deposition within EGR-Heat Exchangers," PhD Thesis, TU Munich, 2012, http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss-20120417-1096402-1-5.
6. Tsai, C.-J., Lin, J.-S., Aggarwal, S.G., and Chen, D.-R., "Thermophoretic Deposition of Particles in Laminar and Turbulent Tube Flows," *Aerosol Science and Technology* 38, no. 2 (2004): 131-139, doi:10.1080/02786820490251358.
7. Lehtinen, K.E.J., Hokkinen, J., Jokiniemi, A.A.J.K and Gamble, R.: "Studies on Steam Condensation and Particle Diffusiophoresis in a Heat Exhanger Tube", *Nuclear Engineering and Design*, Volume 213, Issue 1, 2002, Pages 67-77, ISSN 0029-5493, https://doi.org/10.1016/S0029-5493(01)00453-8.
8. Epstein, N., "Elements of Particle Deposition onto Nonporous Solid Surfaces Parallel to Suspension Flows," *Experimental Thermal and Fluid Science* 14, no. 4 (1997): 323-334, ISSN 0894-1777. https://doi.org/10.1016/S0894-1777(96)00135-5.
9. Loo, C.E. and Bridgwater, J., "Theory of Thermal Stresses and Deposit Removal," *Powder Technology* 42, no. 1 (1985): 55-65, ISSN 0032-5910. https://doi.org/10.1016/0032-5910(85)80038-3.
10. Lance, M., Sluder, C., Lewis, S., and Storey, J., "Characterization of Field-Aged EGR Cooler Deposits," *SAE*

Int. J. Engines 3, no. 2 (2010): 126-136. https://doi.org/10.4271/2010-01-2091.

11. Salvi, A., Hoard, J., Bieniek, M., Abarham, et.al., "Effect of Volatiles on Soot Based Deposit Layers," in *Proceedings of the ASME 2013 Internal Combustion Engine Division Fall Technical Conference. Volume 1: Large Bore Engines; Advanced Combustion; Emissions Control Systems; Instrumentation, Controls, and Hybrids*. Dearborn, Michigan, USA. October 13-16, 2013. V001T04A003. ASME. https://doi.org/10.1115/ICEF2013-19162.
12. Abarham, M., Hoard, J., Assanis, D., Styles, D. et al., "Modeling of Thermophoretic Soot Deposition and Hydrocarbon Condensation in EGR Coolers," *SAE Int. J. Fuels Lubr.* 2, no. 1 (2009): 921-931. https://doi.org/10.4271/2009-01-1939.
13. Hong, K.S., Park, J.S., and Lee, K.S., "Experimental Evaluation of SOF Effects on EGR Cooler Fouling Under Various Flow Conditions," *Int. J Automot. Technol.* 12 (2011): 813-820. https://doi.org/10.1007/s12239-011-0093-x.
14. Karwa, R., *Heat and Mass Transfer, Chapter 15 - Mass Transfer* (Springer Link, 2020), 1041-1066. https://doi.org/10.1007/978-981-15-3988-6_15, ISBN:ISBN 978-981-15-3988-6
15. Yaws, C.L. and Satyro, M.A., *The Yaws Handbook of Vapor Pressure (Second Edition), Chapter 1 - Vapor Pressure - Organic Compounds* (Gulf Professional Publishing, 2015), 1-314. https://doi.org/10.1016/B978-0-12-802999-2.00001-5, ISBN:ISBN 9780128029992
16. Yaws, C.L., *Transport Properties of Chemicals and Hydrocarbons, Chapter 10 - Diffusion Coefficient in Air - Organic Compounds* (William Andrew Publishing, 2009), 407-496. https://doi.org/10.1016/B978-0-8155-2039-9.50015-6, ISBN:ISBN 9780815520399
17. Yaws, C.L. and Dang, L.L.X., *Transport Properties of Chemicals and Hydrocarbons, Chapter 3 - Viscosity of Gas - Organic Compounds* (William Andrew Publishing, 2009), 1-92. https://doi.org/10.1016/B978-0-8155-2039-9.50006-5, ISBN:ISBN 9780815520399
18. Yaws, C.L.: "Transport Properties of Chemicals and Hydrocarbons, Chapter 5 - Thermal Conductivity of Gas - Organic Compounds", William Andrew Publishing, 2009, Pages 201-291, ISBN 9780815520399, https://doi.org/10.1016/B978-0-8155-2039-9.50010-7.
19. Janssen, C., "Möglichkeiten zur Prädiktion von unverbrannten Kohlenwasserstoffen in einem direkteinspritzenden Ottomotor," PhD Thesis, Universität Rostock, 2010, https://doi.org/10.18453/rosdok_id00000635.
20. Mosbach, S., Kraft, M., Zhang, H.R. et al., "Der Weg zu einem detaillierten Rußmodell für Verbrennungsmotoren," *MTZ Motortech Z* 70 (2009): 408-412. https://doi.org/10.1007/BF03225493.
21. Sluder, C., Storey, J., Lewis, S., Styles, D. et al., "Hydrocarbons and Particulate Matter in EGR Cooler Deposits: Effects of Gas Flow Rate, Coolant Temperature, and Oxidation Catalyst," *SAE Int. J. Engines* 1(1):1196-1204, 2009, https://doi.org/10.4271/2008-01-2467.
22. Hoard, J., Giuliano, J., Styles, D., Sluder, S. et.al., "EGR Catalyst for Cooler Fouling Reduction", in *Diesel Engine-Efficiency and Emissions Research Conference*, Detroit, MI, August 2007.
23. Lance, M., Storey, J., Lewis, S., and Sluder, C., "Analysis of Lacquer Deposits and Plugging Found in Field-Tested EGR Coolers," SAE Technical Paper 2014-01-0629 (2014). https://doi.org/10.4271/2014-01-0629.
24. Heintz, A., *Thermodynamik der Mischungen* (Springer Berlin Heidelberg, 2017). http://dx.doi.org/10.1007/978-3-662-49924-5
25. Abd-Elhady, M.S. and Malayeri, M.R., "Asymptotic Characteristics of Particulate Deposit Formation in Exhaust Gas Recirculation (EGR) Coolers," *Applied Thermal Engineering* 60, no. 1-2 (2013): 96-104, ISSN 1359-4311. https://doi.org/10.1016/j.applthermaleng.2013.06.038.

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Definitions/Abbreviations

d - Tube diameter
$j_{cond.}$ - Condensation mass flux
p_{sat} - HC vapor saturation pressure
D - Diffusion coefficient
M - Molar Mass
R - Molar gas constant
Re - Reynolds number
Sc - Schmidt number
Sh - Sherwood number
T_W - Wall temperature

Greek Symbols

η - Dynamic gas viscosity
ρ - Gas density
ρ_{HC} - HC mass concentration in the gas stream
$\rho_{HC,s}$ - HC mass concentration above the liquid surface

Abbreviations

HC - Hydrocarbons
TGA - Thermogravimetric analysis

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