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Review on Numerical Analysis of EGR Cooler

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ABSTRACT
With increasing pollution worldwide, the emission standards for diesel engines has become more stringent. The Euro 6 limits the NOxemission from diesel engine to 0.08 g/Km. The current paper presents the various analysis method of EGR cooler operating under different conditions. The primary causes of EGR failures i.e. fouling is also studied by various scholars. The numerical method (CFD) encompassing 1D geometry and experimental techniques of evaluating EGR cooler is also studied. The effect of geometry, material and operating conditions on performance of EGR cooler are investigated by various scholars and the results obtained by such tests are also presented.

KEYWORDS: *EGR cooler, CFD, NOxEmission*

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I. INTRODUCTION

Due to its harmful effects on the environment and human health, many countries have enforced stringent legislation on diesel engine emissions [1,2]. In order to satisfy the requirements of the regulations, NOx and soot emissions must simultaneously be reduced, and exhaust gas recirculation (EGR) is one method of achieving this goal.EGR technology reduces NOx emission by lowering the flame temperature in the cylinder and the oxygen concentration. Cooled-EGR technology has been used to further reduce the rate of NOx emission [3,4].

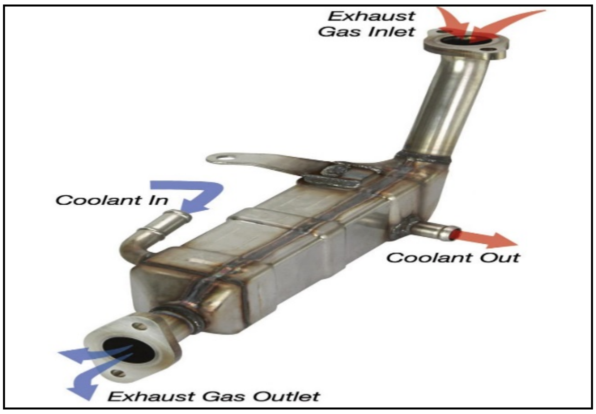

Figure 1: EGR cooler used in automobiles

II. literature review

The thermal effect is influenced by a high concentration of particles in the EGR gas, where the particles may deposit on the wall of the EGR cooler, a phenomenon termed EGR cooler fouling. EGR cooler fouling reduces the efficiency of heat transfer by the heat exchanger, thereby increasing the emission of NOx [5–7].

Hoard et al. reported that the soot deposits in EGR coolers cause significant degradation of the heat transfer efficiency, often on the order of 20−30% [5]. Deposits also increase the pressure drop across the EGR cooler, resulting in an unsatisfactory EGR rate and engine efficiencies under some operating conditions [6,7].

Forthisreason,EGRcoolerfoulinghasbeenwidelystudiedwithrespecttovariousparameters[8–14]. Such studies show that fouling phenomena related to the mass of volatile and non-volatile deposits may be affected by the thermal conductivity of the cooler material and the deposit composition [8], and by the cooler geometry (i.e., cylindrical and finned tube [9] structures) and the inner structure of the cooler [10], which may have limited thermal resistance as heat exchangers [11]. The layout of EGR systems must be optimized by considering the mass flow rate and coolant temperature [12–14]. However, most previous studies have focused on experimental analysis of the effects of EGR cooler fouling on the performance of the engine and NOx emission. Further, it is difficult to evaluate the effect of variables on fouling of the EGR cooler because several variables are coupled to each other. Therefore, fundamental investigation of the apparent interactions between such parameters is important for understanding EGR cooler fouling. In our previous research, a laboratory experiment was conducted by using a PM generator [15] that offers the advantage of independent control of various variables that cannot be controlled in the engine-bench experiment. However, it is difficult to completely replicate the exhaust gas of the engine under various engine conditions

The investigations of B. Ismail [16] and Abarham et al. [17], which proposed 1-D models that investigate the soot deposit evolution considering only the effect of particulate matter deposition mechanisms, are included in this category.

Ismail [16] developed a simplified model, based on two-phase gas-particle conservation equations, which simulates the heat transfer, pressure drop, and soot deposition in EGR cooling devices. This model takes into consideration the particle transport due to the effect of diffusion and thermophoresis and employs a quasistatic-state formulation that computes the incremental deposited layer thickness along the heat exchanger. It allows the prediction of the change in soot layer thickness, the evolution of the temperature at the outlet of the heat exchanger, and the increase in pressure drop across the EGR cooling device. The weak point of this simplified model is that, although it allows the prediction of the main effects of the soot deposit on the cooler performance, its results were not validated with experimental data.

Abarham et al. [17] permits to simulate the cooler effectiveness degradation and pressure drop along the EGR cooler, taking into account the particulate matter deposition caused by the thermophoretic effect. This numerical approach allows the calculation of the reduction of the cross-sectional area of the tube and estimates the evolution of the temperature of the soot layer interface. In this case, the results of this 1-D model were verified using the experimental measurements of a controlled EGR cooler fouling test, and, although the predicted values for the EGR cooler effectiveness were in agreement with experimental data, the values expected in pressure drop differed significantly from the experimental measurements.

Abraham et al. [18] added to their model the simulation of the HC condensation, and this new model belongs to the third group, i.e., the category of 1-D models that take into account both the prediction of the HC condensation and the deposition of soot particles. This numerical approach incorporates, coupling with the soot particle deposition equations, the calculation of the dew point and the total mass flux of HC that condenses and becomes part of the deposit. As their other model, it allows to compute the cooler efficiency degradation and the pressure drop evolution neglecting the changes in the physical structure and the chemical reactions that occur in the fouling layer due to the presence of condensate.

Kern and Seaton [19], which determined that the net growth of the fouling layer depends on two opposing simultaneous processes of deposition and removal, the models of this category recreate the effects of the fouling deposit on the EGR cooler performance.

Reza Razmavar and Reza Malayeri [20] simulated removal mechanisms such as the shear force, the effect of incident particle impact, or the particle rolling, allowing to estimate the gas maximum critical velocity to compute the particle removal flux. The other removal approach is quite different, and it is based on empirically derived removal functions that allow the estimation of the removal trend. In this removal approach, as the one proposed by Sul et al. [21], the equation that computes the removal rate is a function of different parameters, such as the deposit thickness, the temperature, or the pressure drop, and it was derived from the data of experimental tests that cover a wide range of fouling conditions.

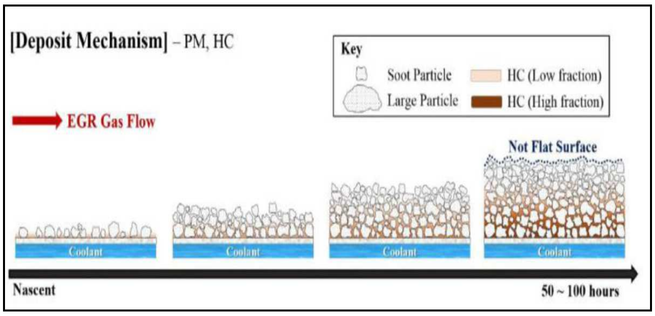

Figure 2: Deposition mechanism with hydrocarbon gradient [21]

The models proposed by Xu et al. [22] and Nagendra et al. [23] use this technique in order to compute the submicron particle deposition inside plate-and-fin heat exchangers. They evaluated the particle deposition under different boundary conditions and validated their results, achieving a good agreement with the experimental measurements taken from literature.

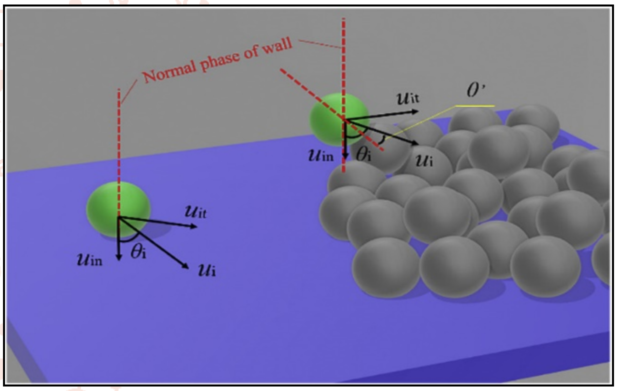

Figure 3: Submicron particle deposition [22]

An example that uses this modeling approach is the study proposed by Yang et al. [24]. In order to estimate the corrosion inside the EGR system of heavy-duty trucks, they developed a numerical technique that determines the condensation of nitric and sulfuric acid. The model allows the carrying out of three-dimensional heat and mass transfer processes simulations, computes the, and calculates the amount of condensate formed on the heat exchanger walls. Using the Ansys Fluent CFD code, it computes the condensation flux of water vapor, sulfuric acid, and nitric acid, providing results under different operating conditions.

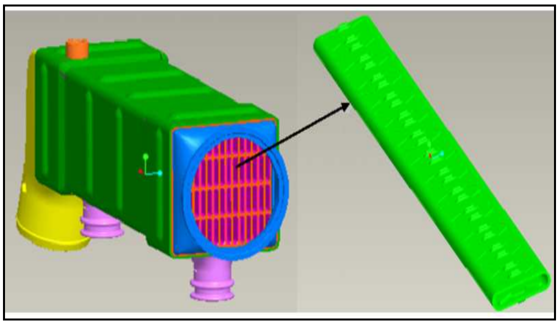

Figure 4: Typical EGR cooler used in off-highway trucks [24]

To recreate the fouling layer growth, the models of the second subcategory employ the dynamic mesh methodology, as the 2-D axisymmetric model proposed by Abarham et al. [25] or the 3-D model proposed by Paz et al. [26– 28]. After the fouling thickness calculation, these numerical approaches adjust the thickness of the deposit moving the fouling-fluid interface. After the fouling thickness calculation, these numerical approaches adjust the thickness of the deposit moving the fouling-fluid interface.

III. CONCLUSION

Various researches are conducted to investigate the causes of fouling and its effect on heat transfer efficiency of EGR cooler. The studies have shown that soot deposition in EGR coolers results in nearly 30% reduction of efficiency. Moreover, several variables which causes the fouling(due to coupling) and it becomes difficult to identify single variable. The 3-dimensional CFD simulation is an effective technique to determine heat and mass transfer processes.

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