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Deposition effect of carbon deposits on charge flow in EGR valve equipped CI engine

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The exhaust gas recirculation (EGR) valve regulates the exhaust gas flow between the engine exhaust manifold and the inlet one. This allows the inlet air to warm up, improving fuel evaporation and reducing the combustion temperature of the charge. Such a valve reduces the number of harmful substances in the exhaust gases. The valve tends to stick when too much sediment builds on the walls of the exhaust system, especially during driving in urban conditions or when leaks in the vacuum or exhaust pipes occur. A faulty valve causes the engine to run unevenly at idle speed and under light loads. The defective EGR valve weakens the inlet manifold capacity, increases combustion, causes clogging of the particulate filter and damage to the lambda probe. Blocked EGR valve may lead to engine immobilization as a result of its computerized control system operations. A model of an EGR valve for a selected diesel engine was developed to determine velocity distribution of the load flowing in it for different values of the degree of valve opening and the volume of deposits on the valve walls. The volume of accumulated carbon deposits on the walls of the EGR valve was measured using a real engine. Based on the recorded mileage of the vehicle, the assumed average speed of the car and the driving style of the driver and the intensity of deposition of carbon particles on the walls was estimated.

Key words: *CI engine, EGR valve, carbon deposits, CFD analysis*

1. Introduction

The necessity of NO_x emission reduction for different combustion engines caused the development and the common use of various catalytic converters and exhaust gas recirculation systems (EGR). The latter allows for recirculation of a portion of exhaust gases from the exhaust manifold and the inlet manifold via a condenser. During the flow, the exhaust gases are gradually cooled down and the deposition of particulate matter, hydrocarbons, and other entrained species takes place [1]. The deposited particles have forms differing in size and chemical composition depending on the place of deposition: on inner walls of EGR system components such as manifolds, pipes, valves, and coolers. The mentioned size and chemical composition of carbon deposits in the case of spark-ignition (SI) engines supplied with gasoline [2] significantly differ from these in case of compressed-ignition (CI) engines supplied by diesel fuel [3], emulsion fuel [4] or biodiesel [5].

The chosen EGR valve, applied in the compressed ignition (CI) combustion engine is shown in Fig. 1. The inlet gas flows from the EGR cooler and outlet gas are directed to the intake manifold of the CI engine. The EGR rate is controlled by balancing the opposing effects of the electric valve drive and the return spring. The inner walls of the EGR valve are covered with carbon deposits (CDs), affecting the loading of the engine exhaust catalysts during their operation. The presented study is aimed to determine the effect of carbon deposits on the inner surfaces on the charge flow inside the EGR valve applied to the CI engine chosen.

1.1. Role of EGR technology

Exhaust gas recirculation (EGR) is an emission control technology decreasing NO_x emission in various CI engines: from light-duty engines through medium and heavy-duty engine to low-speed, two-stroke marine engines [6].

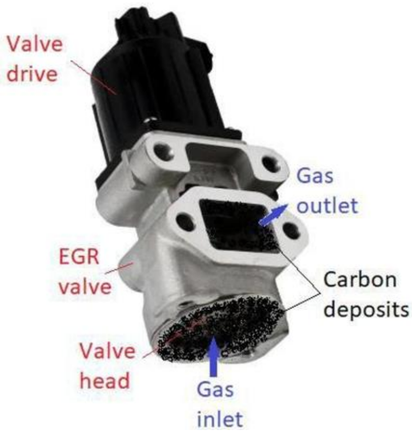

Fig. 1. EGR-valve covered with Carbon Deposits (CDs)

EGR technology is also utilized for enhancing the performance of selective catalytic reduction (SCR) catalysts [7].

Three main NO_x reduction technology pathways are applied in the modern CI engines [6]:

- EGR (without NO_x after treatment),
- EGR combined with SCR after treatment,
- SCR only, without EGR.

EGR systems can be used in HCCI [8] and PCCI engines [9] and in CI engines applied in hybrid vehicles [10–13].

The EGR rate is usually calculated from equation (1) [14]:

$$\text{EGR rate }(\%) = \frac{\text{EGR amount}}{\text{Intake air+EGR amount}} \times 100\% \qquad (1)$$

1.2. Types of EGR systems

There are different classifications for EGR systems. In a hot EGR system, the gas is recycled directly. The EGR-cooler system utilizes a gas-coolant heat exchanger for the operation.

The EGR systems in turbocharged CI engines, depending on the recirculation location, have either high or low pressure loop [15].

The examples of EGR systems utilized in CI engines are presented in Fig. 2, namely: Short-Route-system (SR) (Fig. 2a), Long-Route-system (LR) (Fig. 2b), Hybrid system (Fig. 2c), Venturi system (Fig. 2d), Fast rotating valve system (Fig. 2e) and Pump EGR-system (Fig. 2f) [16]. The EGR valve presented in Fig. 1 has been applied in the Long-Route-system (LR).

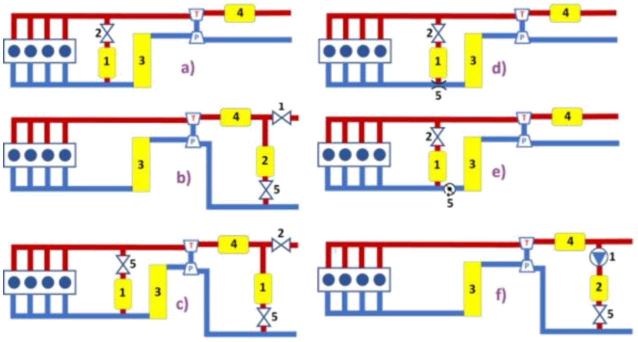

Fig. 2. Example EGR-Systems for CI engines [16]. a) Short-Route-system (SR), 1 – EGR-cooler, 2 – EGR-valve, 3 – Charge Air Cooler (CAC), 4 – Diesel Particulate Filter (DPF); b) Long-Route-system (LR), 1 – Exhaust throttle, 2 – EGR-cooler, 3 – CAC, 4 – DPF, 5 – EGR-valve; c) Hybrid system, 1 – EGR-cooler, 2 – Exhaust throttle, 3 – CAC, 4 – DPF, 5 – EGR-Valve; d) Venturi system, 1 – EGR-cooler, 2 – EGR-valve, 3 – CAC, 4 – DPF, 5 – Venturi; e) Fast rotating valve system, 1 – EGR-cooler, 2 – EGR-valve, 3 – CAC, 4 – DPF, 5 – Fast rotating valve; f) Pump EGR-system, 1 – Pump, 2 – EGR-cooler, 3 – CAC, 4 – DPF, 5 – EGR-valve

Reinfarth [16] discussed the advantages and the drawbacks of the mentioned systems.

The Short-Route System (SR) is simple and responds fast to EGR demands. It needs throttling and is sensitive to soot deposition in the whole intake system. It also needs the turbocharger able to deliver sufficient charging pressure, as only part of the exhaust gas passes the turbine while another part is used as EGR.

In Long-Route-system (LR), the compressor and the charge air cooler are in contact with the exhaust gases. The optimization of the cooling effect of the EGR-cooler prevents any condensation that would be able to damage the compressor wheel. The latter is exposed to exhaust gases accelerating its corrosion.

To avoid clogging in this system the EGR-loop is placed downstream from the particulate filter. To generate the pressure drop needed to drive the flow of EGR throttling the exhaust or the intake air is applied, however, the former manner is preferred due to lower fuel consumption.

The LR-system utilizes long piping filled with EGR causing a delayed reaction to changing EGR demands. Additionally, the exhaust gas with soot particles after the diesel particulate filter (DPF) causes fouling of the intercooler.

Such a system increases mass flow passing through both the turbine and the compressor. Under low loads, this limits the engines fuel consumption as compared to the SR-system. Such a consumption is also decreased due to the higher cooling capacity of the LR-system. As the EGR is cooled by the cooler and by the intercooler, the intake temperatures for the LR-system are lower and thus the heat losses in the engine are minimized.

The Hybrid EGR system allows the application of the EGR-path best fitting the actual driving situation and to reach the best engine efficiency in certain load points.

The Venturi system allows for local increase in the pressure drop that drives the EGR flow. In this system, the pumping effect can be regulated. A higher pumping effect with more EGR flow increases the pressure in the intake piping.

In the EGR system with Fast Rotating Valve, the pressure drop driving the EGR is increased via throttle of the intake air. However, this limits the intake pressure and enhances the pumping resistance. Simultaneously the delivered amount of air decreases, weakening the tolerable EGR rate. This problem is resolved via the application of a system with a fast-rotating throttle, limiting the intake pressure temporarily for better EGR performance, while keeping low values of the average pressure. The intake air pressure is limited just in time for the exhaust pulses to press some EGR into the intake.

The EGR system with the pump can supply the desired amount of EGR in any driving situation without any throttling. It needs an additional energy to drive a pump resulting in higher fuel consumption. Electric drive allows its speed regulation independently from the engine speed. The design of each EGR system is complex and requires [17]:

- limiting the pressure drop of the cooler, particularly in low-pressure-loop EGR systems,
- the compactness requiring high thermal efficiency,
- limiting the coolant flow rate to prevent its boiling,
- a careful thermal fatigue cycle analysis due to difficult and variable operating conditions,
- prevention of unexpected structural failures resulting from pressure pulses in the exhaust gases promoting fluctuating forces,
- limiting the negative effect of the deposition of residue on heat transfer walls, on the gas side and on the thermal efficiency

1.3. Effects of EGR

The use of EGR results in various effects on engine operation and phenomena generated therein. EGR valve is placed in the airpath chain of a combustion engine and routes usually more than 10% of the exhaust gas (or mixture), from the exhaust manifold, back into the inlet one [18].

Such a valve doses the appropriate amount of exhaust gas into the inlet manifold, relative to the engine load and speed. The location of the EGR valve causes diverse formation of NO_x and fumes smokiness from the individual cylinders of the engine, due to an uneven propagation of exhaust gas into the channels of the inlet manifold [19].

Mulenga et al. [20] reported that cooled EGR decreased in-cylinder NO_x formation. Abarham et al. [21] noticed that EGR coolers are usually cooled with engine coolant.

Agarwal et al. [22] explained that EGR controls the NO_x in CI engines via the lowering the O_2 concentration and flame temperature of the charge in the combustion chamber. Higher soot generated by EGR leads to higher carbon deposits, lubricating oil degradation and enhanced engine wear.

Pulkrabek [23] reported that EGR allowed better fuel economy and more efficient drivability. Okubo and Kubahara [24] noticed that EGR weakening NO_x emissions, fuel consumption and pumping loss is suitable for diesel engines with large exhaust gas flow rates. Hussain et al. [25] reported that EGR increased the UHC emission by 40 to 50%. Such an effect is avoided by reutilization of UHC. Parks et al. [9] found that the fuel efficiency and emission of PCCI engine depend on the EGR rate, fuel rail pressure, and fuel injection timing. As EGR enhanced, NO_x emission decreased, but CO and HC emission increased. The emission and efficiency changed significantly as EGR rates increased above 40%. As the EGR rates grew, the fuel efficiency began to drop, and the engine operation became less stable. Simultaneously, CO and HC emission rose due to the instability as incomplete combustion occurred

2. Charge flow in the EGR system

In the literature [26–28], the charge flow in an EGR system is usually considered as an integral part of the charge flow throughout the engine. Only a few papers consider the problem of disturbances in such a charge flow resulting from the presence of fouling of carbon and soot deposits.

Abd-Elhady et al. [29] reported that EGR coolers were affected by severe fouling resulting in the drop of their thermal efficiency by up to 30% within a very short period. The deposited layer was a blend of particulate matter and sticky heavy HCs difficult to remove from the heat exchanger surfaces.

Some authors [30, 31] noticed that the use of the EGR cooler results in higher production of PM.

According to [32–34] EGR operation affects the combustion, and hence NO_x formation and reduction via three mechanisms decreasing the flame temperature:

– dilution: the potentially enhanced mixing time and longer burn duration caused by the EGR's dilution effect. Additionally, the EGR weakens the partial pressure of O_2, due to lower temperature and low availability of O_2 less NO_x is produced,
– thermal: the enhanced heat capacity of an EGR-laced mixture,
– chemical: enhanced dissociation of CO_2 and H_2O,
– Exhaust gas from engines is cooled to decrease the emission via the EGR cooler.

Kowada et al. [35] reported that the use of a catalyzed wall-flow DPF allows limiting PM emission in both mass and small particles. Abarham et al. [36] reported that the soot and hydrocarbon deposition in the EGR cooler may be acidic and corrosive.

Some authors [37, 38] reported that EGR fouling exhibited an asymptotic evolution characterised by the rapid growth of the deposited layer in the first stages and a progressively slower growth until stable conditions are reached.

Authors of refs. [39, 40] noticed that the duration of the entire fouling process generally covers a matter of hours causing the EGR system operation almost its entire lifetime under fouled conditions.

As reported in [41, 42] the deposition of fouling material on heat transfer walls enhanced the thermal resistance due to the low conductivity of the residue.

Hoard et al. [43] reported that the thickness of the deposited layer, soot and hydrocarbons primarily limited the free-flow section, changing the velocity field, boundary layer separation and reattachment locations, compared to clean conditions, and changes in the turbulence field.

Hesselgreaves [44] stated that such changes enhanced the gas pressure drop through the cooler.

Williams et al. [45] explained that the carbon-containing deposits such as the particulate matter, hydrocarbons, and other entrained species having deposited from the flow of exhaust gas cooling down, form in the EGR systems. Reduction of such deposits needed optimized dimensioning of EGR coolers and valves, the use of EGR cooler bypass in the most sensitive cold conditions and the use of oxidation catalysts upstream of the EGR system. CDs forming in the HP-EGR systems caused emission and fuel consumption deterioration, poor performance and drivability, as well as engine failure. It was also report-ed that in the HP-EGR system of a CI engine operating at conditions conducive to EGR deposit formation over 24 hours, such a formation with Fischer-Tropsch Gas-to-Liquid (GTL) Gasoil fuel was less by 72% than that with B7 representative of EN590 diesel fuel.

Tanaka et al. [46] reported that the formation of lacquer with soot on the EGR valve or cooler occurred at 100°C or less, but not at 120°C. After the engine start, water was detected during the initial period for all temperatures studied. After the evaporation of water, aromatic HCs occurred at lower temperatures, while C=O groups occurred at higher temperatures.

3. Modelling of fouling and deposition of carbon and soot deposits

3.1. Models of fouling and deposition of carbon and soot deposits

There are some models created to solve the problem of fouling as well as the deposition of carbon and soot, which are strictly related.

Teng and Regner [47] elaborated a model for soot particle deposition. The soot deposit comprised three characteristic layers:

– a quasi-crystal base layer formed by nanoparticles,
– an intermediate layer of denser packing of soot particles with mesopores,
– a highly porous top layer formed by mechanical interlocking of soot particles.

The EGR performance was affected by the top layer of the deposit. The low contact energy made particles in the top and intermediate layers removable by the shearing force under high EGR flows. The contact energy for the particles in the base layer was much higher compared to that in the surface and intermediate layers.

The behaviour of the EGR cooler fouling at the transient engine operation differed from that at the steady-state conditions.

Abarham et al. [36] developed a 1-D model to determine EGR cooler fouling amount and distribution across a concentric tube heat exchanger with a constant wall temperature in the CI engine. It well predicts the effectiveness, mass deposition, and pressure drop.

Jafarmadar et al. [48] used the model of the soot formation rate treated as the difference between the soot formation and oxidation, given by the equation (2).

$$\frac{Dm_{soot}}{dt} = \frac{dm_{form}}{dt} - \frac{dm_{oxid}}{dt} = A_f \cdot m_{fv} \cdot p^{0.5} \cdot \exp\left(-\frac{E_a}{R \cdot T}\right) - \frac{6 \cdot M_c}{\rho_S \cdot d_S} \cdot m_s \cdot R_{tot} \quad (2)$$

where: A_f – constant, R – gas constant, T – temperature, p – pressure, E_a – energy of activation, m_{fv} – mass of fuel vapour, m_s – mass of soot, M_c – molecular weight of carbon, ρ_s – soot density, d_s – soot particle size, R_{tot} – soot oxidation rate.

Some models of the fouling process in the EGR cooler system utilize a 1D approximation of the geometry and usually comprise no erosion or re-entrainment mechanisms [36, 49].

Other models utilize a Lagrangian framework for particle transport on a simplified channel of the heat exchanger [50].

Sometimes a complete steady 3D model applied to a single tube us used [51].

The model elaborated by Abarham et al. [49] predicts well a fouling depth. Most of the methods and models are based on bulk conditions or non-local parameters and applies only to simple geometries (1D, axisymmetric, single-channel, etc) where the homogeneity of the flow allows easy definition of those parameters.

3.2. Paz et al. fouling model

From the point of view of modelling of fouling in the EGR valve, the model developed by Paz et al. [52, 53] and presented in Fig. 3 seems to be very useful.

The model is based on the deposition-removal balance, and properly predicts the local fouling thickness under the constant thermal and flow conditions.

It adapts the fouling model [54] based on soot particle deposition neglecting the condensation and considered local effects.

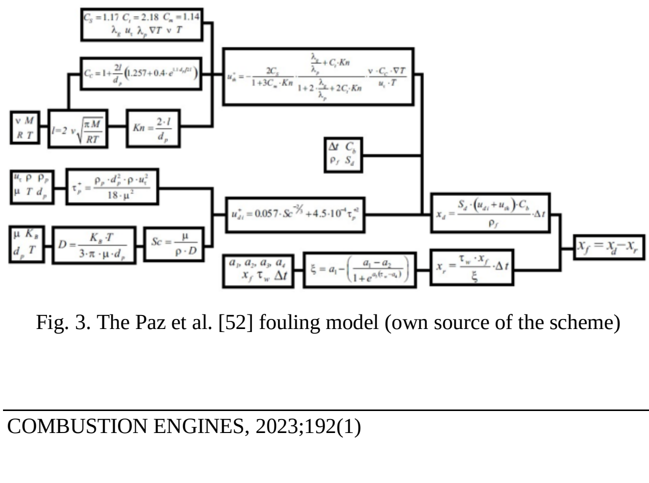

Fig. 3. The Paz et al. [52] fouling model (own source of the scheme)

In the model the sticking probability S_d is equal to one, and the bond strength factor ξ is adjusted experimentally. The model comprises dimensionless deposition and removal velocities. The deposition velocity is the sum of mass diffusion u_{di}^+ and thermophoresis u_{th}^+, which is the highest deposition force when thermal gradients occur [55] with typical soot particle sizes between 10^{-8} to 10^{-5} m [56].

The re-entrainment of deposited particles is quantified via the average velocity or shear stress at the wall [40, 57–59].

The removal dimensionless velocity is proportional to the layer thickness and the wall shear stress [60–62].

After determining the velocities for each cell, the net fouling thickness x_f is determined at the end of the time step. Such a thickness is then accumulated in the cells adjacent to the walls until the height of a cell is exceeded, and then the fluid cell is changed to a solid one with its corresponding physical properties. Such a process is reversible, allowing a fouled cell to become a fluid cell again if the flow conditions change and the newly computed x_f is smaller than the cell size. The deposit properties include an effective density of 36.5 kg/m^3 and thermal conductivity of 0.07 W/m·K [52].

The fouling factor evolution curves are fitted to the asymptotic profile and the deposit mass is weighted under 30 to 60 kg/h exhaust gases flow at 400ºC [53]. Such a methodology allows for time reconstruction of fouling.

3.3. Adaptation of the Paz et al. fouling model to the case of the EGR valve fouling

To adapt the Paz et al. fouling model to the case of the EGR valve fouling it was necessary to do some transformations and make some assumptions.

The assumed dimensionless dependency of the average fouling thickness h/h_{ref} versus mass flow in EGR valve $\dot{M}/\dot{M}_{ref}$ was similar to the one for the average fouling thickness versus tube mass flow [63] (Fig. 4).

The assumed dimensionless dependency of the CD mass in the EGR valve m^{CD}/m_{ref}^{CD} versus time t/t_{ref} is similar to the one for the CD mass in EGR cooler versus time [63] (Fig. 5).

In these dimensionless dependencies the following symbols occurred: $\dot{M}_{ref}$ – the EGR inflow mass flow, $t_{ref} = L/V_{aver}$ – time of car mileage, L = 172,000 km – car mileage, V_{aver}= 60 kph – average car driving speed, $h_{ref} = V^{CD}/A$ – average fouling thickness in EGR valve, V^{CD} – calculated CD volume, A – the calculated area of inner walls of the modelled EGR valve, m_{ref}^{CD} – measured CD mass in the EGR valve after reaching the assumed car mileage.

For the actual EGR gas mass flow $\dot{M}$ the average fouling thickness h was determined and then actual CD mass $m^{CD} = \rho \cdot A \cdot h$ was estimated, where ρ – EGR carbon deposits density, and then time for CD inside EGR valve was determined. The fitting of the Paz et al. fouling model [52] to the obtained function $h = f(t)$ allows estimating the unknow input model parameters.

The situation becomes easier if the values of some parameters can be determined during separate experimental studies or estimated based on the literature data.

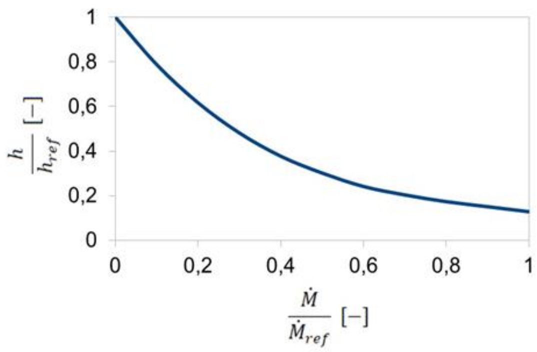

Fig. 4. The average fouling thickness h/h_{ref} vs. mass flow in EGR valve $\dot{M}/\dot{M}_{ref}$

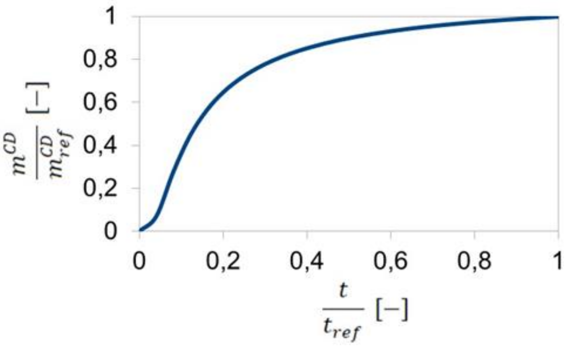

Fig. 5. The CD mass in the EGR valve m^{CD}/m^{CD}_{ref} vs. time t/t_{ref}

4. Methods and materials

4.1. Engine characteristics and operational conditions

During the study, the EGR valve from a CI engine of Opel Zafira 1.7 CDTi was used. The characteristics M(n) and P(n) of such an engine were obtained from the dyno test and are presented in Fig. 6. It was assumed that the engine operated at rotational speed equal to 4000 rpm.

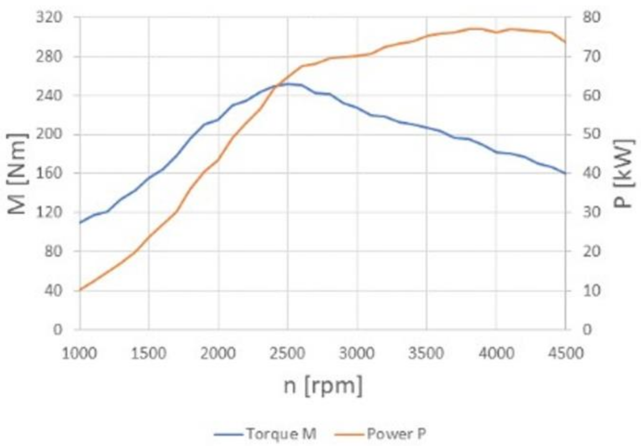

Fig. 6. Characteristics of a CI engine of Opel Zafira 1.7 CDTi (own source)

4.2. CFD model of the EGR valve

To allow the CFD analysis of charge flow in the EGR valve the model of the latter was elaborated. The model of the fluid domain comprising inner volumes of EGR valve (3+4+5–6), part of intake manifold 1 and connecting canal 2 is presented in Fig. 7. As an approximation, for diesel exhaust gas calculations the properties of air were used. The error associated with neglecting the combustion products was below 2%. Air was treated as an ideal gas [64].

The lift of the EGR valve was 3.7 mm (about 30% of full valve opening) corresponding to the EGR rate in the range 30–40%, similarly to the system described in [65].

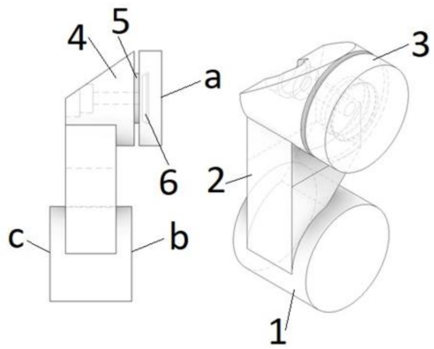

Fig. 7. Model of fluid domain: 1 – intake manifold, 2 – connecting canal, 3 and 4 – the inner volume of EGR valve being the sum of sub volumes, 5 – orifice, 6 – excluding the volume of valve: a – inlet of exhaust flow from EGR cooler, b – an inlet of air, c – outlet of a mixture of air and EGR gas

4.3. Estimation of carbon deposit volume

To consider an occurrence of CDs in the model of the fluid domain (Fig. 7), on the inner surfaces of the connecting canal 2, EGR subvolumes 3 and 4, and on the outer surfaces of the excluded volume of valve 6 the thin layers were added. The thickness of a chosen layer was equal to the average height of the CD structures on the relating wall obtained from optical scanning microscope. The introduced layers (Fig. 8) limited the volume of the flow domain in the model shown in Fig. 5.

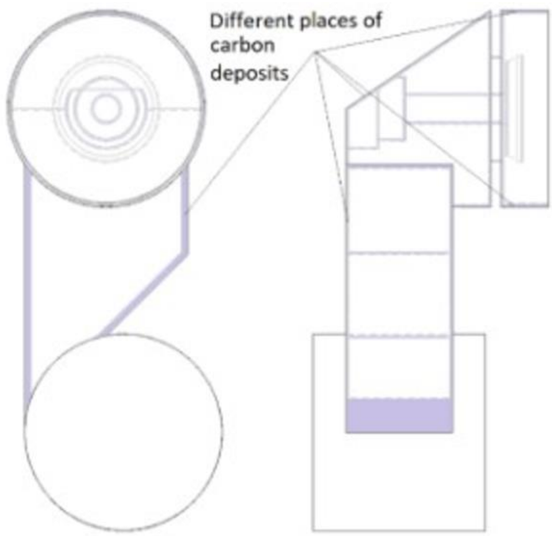

Fig. 8. The corrected model of the fluid domain from Fig. 7 after introducing modelled layers of carbon deposits

4.4. Assumptions and boundary conditions

For the modelled fluid domain, the following assumptions and boundary conditions were introduced:

– a no-slip boundary condition was applied on the walls and a standard wall function option was used for near-wall treatment

- the normal flow velocity of EGR inflow gas (from the EGR cooler) was 18.59 m/s for the case without CDs and 20.13 m/s for the case with CDs. It corresponded to the mass flow rate of 0.038 kg/s, being 30–40% of the mass flow rate in the intake manifold when the EGR rate is 30%, similarly to [66]. The temperature of an inflowing gas was 473 K,
- the normal flow velocity of air from the turbocharger was 44 m/s corresponding to the mass flow rate of 0.09 kg/s and its temperature was 330 K, similarly to the 1.6 L CI engine with variable geometry turbine VGT and Common rail systems [67],
- the outlet flow of the mixture of EGR gas and air was under a pressure outlet boundary condition and temperature of 373 K,
- the temperature of the walls was 373 K and no heat transfer through the walls occurred,
- the fluid flow and heat transfer processes were turbulent and in steady state,
- the mesh comprising tetrahedral finite elements was generated in the fluid domain (Fig. 9), the inflation option was chosen on walls with at least five layers and an average size of an element was 3 mm.

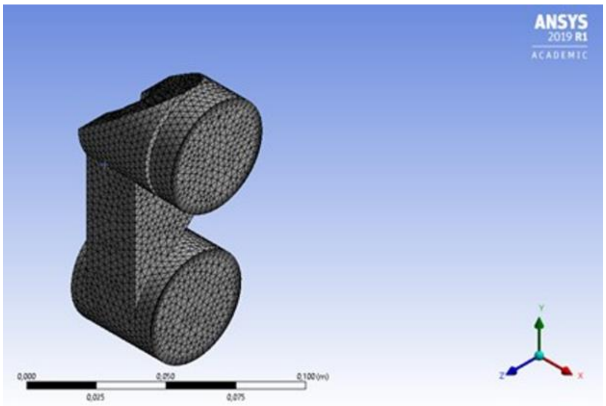

Fig. 9. Mesh of finite elements for the fluid domain of EGR model analyzed

4.5. Carbon deposit thickness

The carbon deposit thickness was estimated by measuring the inner geometry of a new and operated EGR valves with use of optical scanning microscope. An optical scanner, structured light by GOM with an ATOS core head was used for scanning. GOM scan and Geomagic Design X software were used to process the scans. The dimensions were inspected using the GOM Inspect module.

4.6. Carbon deposit mass, volume, and density

Two masses of EGR valves without an electric driver were measured for two cases: of the new valve and the one covered inside with CDs.

The CD volume V^{CD} was calculated as a difference of inner volumes of a new EGR valve and EGR covered by CD layers.

The CD mass m_{ref}^{CD} was calculated as a difference between the measured mass of an EGR valve without an electric driver and covered inside with CDs and the one of a new EGR valve, also without an electric driver.

The CD density ρ was calculated as a ratio of the CD mass and its estimated volume. It was compared with the one of graphite equal to 2.25 g cm^{-3}.

5. Results

5.1. Carbon deposit thickness

The obtained carbon deposit thickness measurement results are presented in Fig. 10. The EGR valve measured on side of the valve stem is depicted in Fig. 10a), whereas in Fig. 10b) is presented the side of the valve head. The average values of thickness visible in Fig. 10a) were even twice higher than these visible in Fig.10b.

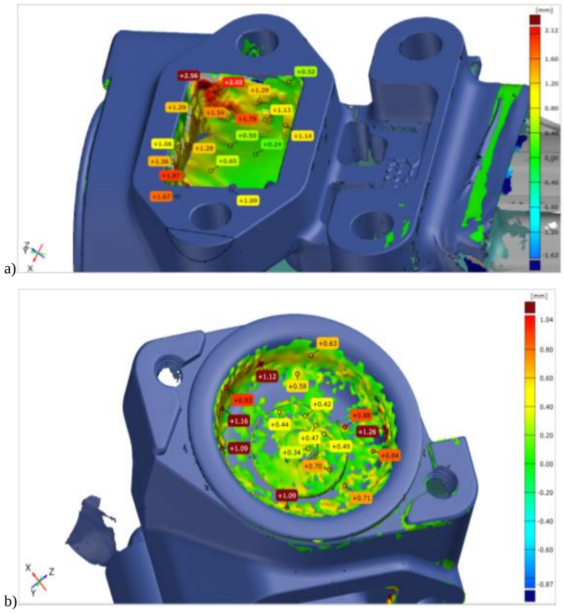

Fig. 10. Thickness of carbon deposits in an EGR valve chamber measured using optical scanning microscopy, a) on side of the valve stem, b) on side of the valve head

5.2. Carbon deposit mass, volume, and density

The masses of EGR valve without an electric drive for two cases: for the new valve and the one covered inside with CDs, the CD mass, CD volume and CD density, the ratio of CD density and that of graphite are presented in Table 1.

The obtained density of carbon deposits inside the EGR valve could be slightly greater than the density of graphite. It was because CDs could contain also other substances than carbon, for example, S, Cl, Ca, and Zn originated from the combustion of lubricating oil [68].

It could be also lower than the density of graphite due to the very uneven and porous structure. Thus, the obtained density of CDs can be treated as the equivalent one.

Table 1. The masses of EGR valve without an electric drive for two cases: the new valve and the one covered inside with CDs, the CD mass, CD volume and CD density, the ratio of CD density and that of graphite

Mass of a new EGR valve	[g]	522.699 ±0.001
Mass of an EGR valve covered inside by CD	[g]	523.669 ±0.001
CD mass	m_{ref}^{CD} [g]	0.97 ±0.002
CD volume	V^{CD} [cm^3]	0.43 ±0.7
CD density	ρ [g cm^{-3}]	2.325 ±0.56
CD density/density of graphite	[–]	1.033 ±0.25

5.3. The flow velocity of charge in the modelled EGR valve

The values of the flow velocity of charge, calculated using the modelled EGR valve are presented in Fig. 11 for the case of the new EGR valve and in Fig. 12 for the case of the EGR valve covered inside by the CD layers. On the left side of each figure is presented the 3D view of the velocity distribution and on the right side the velocity distribution in the XY plane (the orientation of these axes is visible in Fig. 9) containing the main axis of the EGR valve. The values presented in Fig. 12 are higher even by 30% than those in Fig. 11.

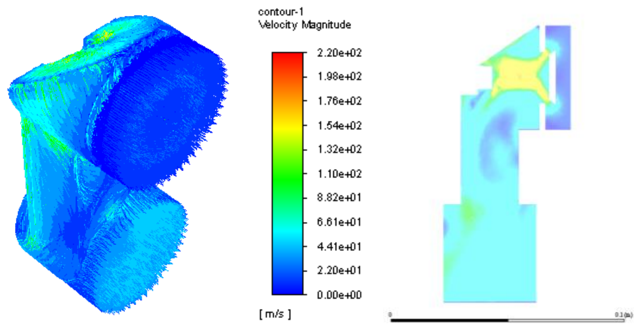

Fig. 11. The flow velocity of the fluid in the new EGR valve

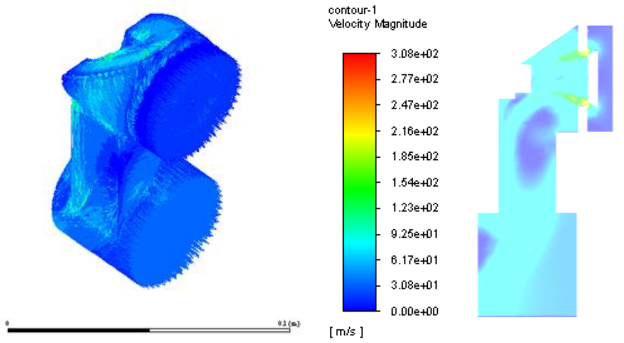

Fig. 12. The flow velocity of the fluid in the EGR valve covered inside by the CD layers

5.4. The total temperature of charge in the modelled EGR valve

The values of the total temperature of charge calculated using the modelled EGR valve are presented in Fig. 13 for the case of the new EGR valve and in Fig. 14 for the case of the EGR valve covered inside by the CD layers. On the left side of each figure is presented the 3D view of the temperature distribution and on the right side the temperature distribution in the XY plane (the orientation of these axes is visible in Fig. 9) containing the main axis of the EGR valve. The values presented in Fig. 14 are higher even by 30% than those in Fig. 13.

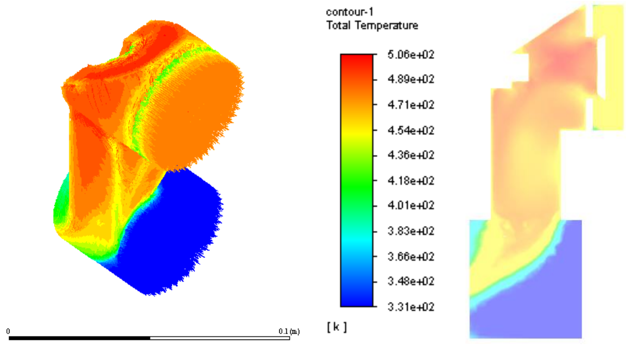

Fig. 13. The total temperature of charge in the new EGR valve

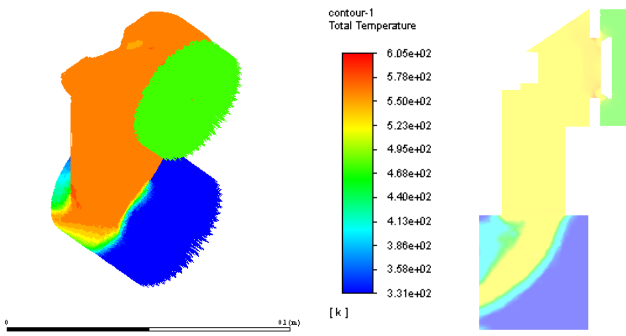

Fig. 14. The total temperature of charge in the EGR valve covered inside by the CD layers

6. Conclusions

Based on the obtained results the following conclusions can be drawn:

- the analysis of the effect of deposition of CDs on the charge flow in the EGR valve in the CI engine was performed,
- only a few models intended for simulation of the fouling process in the EGR system can predict the fouling depth,
- the method allowing determination of the function for average fouling depth inside the EGR valve versus time and the mass flow inside the EGR valve $h = f(t, \dot{M})$ has been proposed. Fitting fouling model of Paz et al. to such a function $h = f(t, \dot{M})$ allows estimation of the model parameters,
- the occurrence of CDs in the EGR valve strongly affects the distribution of the flow velocity of charge therein. The values of the flow velocity when CDs occur can be up to 30% higher than in the case of EGR without CDs,
- the total temperature values of the charge flowing in the EGR valve with CDs can be higher by 100 K as compared to the case without them. In the latter case, the total temperature distribution varies more in value and position than in the case with CDs.

Nomenclature

CI compression ignition
CD carbon deposits
CFD computational fluid dynamics
EGR exhaust gas recirculation
SCR selective catalytic reduction

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