Exhaust Gas Recirculation (EGR) valve, design and computational fluid dynamic analysis

C L Dumitrache¹, B Hnatiuc² and D Deleanu¹
¹ Maritime University of Constanta, Faculty of Electromechanics, Department of General Engineering Sciences, Mircea cel Batran street, No. 104, Constanta, 900663, Romania
² Maritime University of Constanta, Faculty of Electromechanics, Department of Electrical Engineering Sciences, Mircea cel Batran street, No. 104, Constanta, 900663, Romania
E-mail: ldumitr@yahoo.com

Abstract. All EGR systems used on contemporary cars operate on the principle of "external" exhaust gas recirculation. A certain proportion of the engine exhaust gases is extracted and transmitted back into the fresh air-gasoline mixture by means of a control valve. Exhaust gas recirculation valve is generally controlled by a pneumatic or mechanical system designed to dose the exhaust gases in accordance with certain factors such as: engine speed; intake manifold pressure; engine temperature. This paper presents the design steps of the EGR valve using NX SIEMENS. After making the 3D model, it was imported into ANSYS where a study of the flow of fluids (flue gases CO₂ and liquid coolant) was made. In this study it was considered that the valve was actuated and the exhaust gases enter the engine while they are also cooled by the liquid coolant. From the fluid flow modeling process it can be seen that the coolant does not take much of the flue gas temperature, its role being more to maintain a proper temperature of the body valve.

1. Introduction
There are active measures aimed at combating the formation of pollutants (NOx) by optimizing combustion, their effect being focused on the processes in the combustion chamber. Contradictory influences of some factors on the types of legislated pollutants were observed, but also contradictory effects of the same factor on the same pollutant, in the case of different engines. In general, measures to reduce pollutants have led to relatively small increases in fuel consumption, which means finding a compromise [1].

Within the group of listed pollutants (HC, CO, NOx, PT-particles) there is a need for a compromise between NOx values, on the one hand, and PT, CO, HC values, on the other hand. The inverse dependence of these quantities is due to the temperatures developed in the combustion chamber. Measures to reduce NOx and other pollutants simultaneously are relatively few and are usually applied outside the combustion chamber.

The increased amount of waste gas in the cylinder leads to a decrease in the amount of fresh air sucked in, with a decrease in NOx and an increase in smoke; the flue gases remaining in the cylinder reduce the amount of O₂ available, slowing down NOx formation reactions. The favorable influence of waste gases on reducing NOx formation has led to the Exhaust Gas Recirculation method, abbreviated...
EGR, which consists in reintroducing a fraction of the flue gases into the cylinder. Increasing the degree of recirculation is very efficient in terms of reducing NOx.

Using EGR reduces the amount of air in the fresh fluid in the cylinder and there is a tendency to increase the smoke and the duration of combustion, which leads to increased fuel consumption; these trends are stronger with increasing load, so that EGR proves to be a very good measure of NOx reduction, but only under the conditions of proper correlation with engine load and within acceptable limits of increasing fuel consumption [2, 3].

2. Experimental research using EGR systems
A research team [1] designed and executed an EGR installation that tested it on two Romanian engines with different litres 392-L4-DT and 1035-L6-DTI:

2.1. Experimental determinations on the 392-L4-DT engine
The main scheme of the installation is represented in figure 1:

![Figure 1. Engine 392-L4-DT test bench [1].](image)

The exhaust system of the test bench had the possibility to be partially blocked in order to allow a certain part of the flue gases to be recirculated under the influence of pressure differences. The originality of the installation consists in fact that it is built in such a way that it can test engines with different litre’ values, without being dependent on the constructive or functional type of the recirculation valve.

For the measurement of specific quantities, the measuring installations of the test bench were used such as:
- speed transducer;
- gravimetric vessel for determining fuel consumption;
- thermocouples, manometers;
- differential flow meter with laminar element MERIAM.

The flue gas analysis was performed with the BECKMAN 1945-1954 type analysis installation composed of:
- flame ionization detector for unburned hydrocarbons (model 402) HFID;
- infrared absorption analyzer for carbon monoxide (model 854) NDIR;
- chemiluminescence analyzer for nitrogen oxides (model 951) HCLA.

The smoke index was determined with an AVL Dismoke 435 opacimeter. The research aimed to compare some sets of engine parameters:
- pollutant emissions - NOx, CO, HC;
- smoke index;
- fuel consumption;
- performance - engine torque, power

determined in operation, with and without flue gas recirculation.
The degree of recirculation was used as a recirculation parameter. The case without recirculation or with zero degree of recirculation was considered as a reference.

In order to be able to assess the degree of flue gas recirculation, a calibrated diaphragm was used to determine the flow, a calculation that takes into account the procedure described in standard 7347/3 [4]. The mass flow rate was calculated considering the variation of the gas density with temperature.

The flue gas composition, according to [5] was considered as follows: \( \text{CO}_2 = 13\% \), \( \text{H}_2\text{O} = 11\% \), \( \text{N}_2 = 76\% \). The recirculated gas flow, \( \text{D}_g \), measured in [kg/s] was determined with the relation:

\[
\text{D}_g = \alpha \cdot \varepsilon \cdot S \cdot \sqrt{2 \cdot \Delta p \cdot \rho}
\]

where: \( \alpha \) - flow coefficient (\( \alpha = 0.6 \)), \( \varepsilon \) - expansion coefficient (\( \varepsilon = 0.999 \)), \( S \) – diaphragm section (\( S = \pi d^2 / 4 = \pi 28.37722^2 / 4 \)), \( \Delta p \) - pressure drop per diaphragm [mm col \( \text{H}_2\text{O} \)], \( \rho \) - flue gas density [kg/m\(^3\)].

Depending on the desired degree of recirculation, the recirculation pipe was partially blocked from the control valve, and the recirculated flow rate was calculated with the above formula, based on the pressure drop reading. The samples aimed to identify the recirculation effect according to a recirculated gas flow dictated by a recirculation degree (GR) of 10\%, 20\% and 30\%, having as reference the case of zero recirculation. The definition of the degree of recirculation is as follows:

\[
\text{GR} = \frac{D_g}{D_g + D_{\text{air}}} [\%] \tag{2}
\]

where \( D_g \) - recirculated gas flow rate determined by relation (1), and \( D_{\text{air}} \) - fresh air flow rate allowed in the engine [kg/s].

The values of the calculation quantities and the gaseous pollutant emissions were calculated for a degree of recirculation of 0\%, 10\%, 20\% and 30\% respectively, and the reductions of the pollutants are summarized in table 1.

| Pollutant [g/kwh] | GR=0\% | GR=10\% | GR=20\% | GR=30\% |
|-------------------|---------|----------|----------|----------|
| NOx               | 13.4    | 11.0     | 6.2      | 3.2      |
| NOx reduction\[%\] | -       | 17.8     | 54       | 77.6     |
| CO                | 5.8     | 7.1      | 9.7      | 10.4     |
| CO increase\[%\]  | -       | 23.5     | 67.5     | 79.6     |
| HC                | 0.58    | 0.57     | 0.54     | 0.63     |
| HC reduction\[%\] | -       | -1.7     | 6.8      | -8.6     |
| Particle PT       | 0.7     | 0.9      | 1.7      | 2.4      |
| Particle PT increase\[%\] | -     | 17.6     | 135      | 229      |

\* in percentage compared to GR = 0\%

The NOx reduction potential was confirmed by recirculating the flue gas using the described experimental installation. The NOx reduction is considerable, up to 77\%, which is a lot for this pollutant.

Flue gas recirculation leads to a significant increase in particles and CO emissions. Overall, reducing NOx is more important than increasing other pollutants because they can be reduced by a passive method outside the engine, for example by using the oxidation catalyst.
2.2. Experimental determinations on the 1035-L6-DTI engine

The research was similar to the previous one with the observation that the engine had cylinders of 10.35 litres, being supercharged and having intermediate cooling, and the recirculation installation included a recirculated gas cooler, positioned as in figure 2:

![Figure 2. Engine 1035-L6-DTI test bench [1].](image)

The behaviour of the system at different speeds was investigated, choosing for example the results from the speed of 1600 rpm processed in figure 3; it can be seen how NOx emissions decrease with increasing recirculation and how smoke (“fum” in the figure 3) emissions increase; the cooling of the recycled gases maintained the performance gain of the engine resulting from the application of the intermediate cooling of the intake air.

The most important conclusions of the research are [1]:

![Figure 3. The correlation between NOx and smoke (Fum) versus engine torque M [1].](image)
Gas-cooled recirculation is an effective NOx-lowering technique if a few precautions are taken to avoid increasing smoke. The largest decrease in NOx occurs at high recirculation levels, which increases the emission of smoke and CO. For a degree of recirculation of 20% with the cooling of the flue gases that varies depending on the load from 220-490°C to 50-60°C an average decrease of NOx of 46% is obtained.

- Even if the CO increases for a recirculation degree GR = 20%, its level does not exceed the EURO III pollution limit. At low loads below 50%, recirculations of 20% can be practiced, at higher loads, no.
- HC emission is less sensitive to varying degrees of recirculation.

3. The CAD models of EGR parts
The idea of writing this article started from the change of the EGR valve from the personal car (figure 4). Having the piece in my hands, I measured the overall dimensions and the other dimensions inside the piece, then, I translated them into a 3D model made with NX SIEMENS. This valve is found on almost all current cars that have gasoline and diesel engines.

In the Service and Repair Manual [6] is written that the system is designated to recirculate small quantities of exhaust gas into the inlet tract, and therefore into the combustions process. This process reduces the level of unburnt hydrocarbons present in the exhaust gas before it reaches the catalytic converter. The system is controlled by the fuel-injection/emission control unit (ECU) using the information from its various sensors, via the EGR valve. On 1.4 litre model, EGR valve is an electrically-operated valve mounted on the inlet manifold or the left-hand end of the cylinder head.

When designing this valve using NX Siemens, all the dimensions measured directly on the real part were taken into account. The valve has been designed in parts such as:
- body valve;
- electrical coil through which the valve is actuated;
- the connector through which the valve is electrically operated;
- short pipe to which the hose through which the coolant passes is connected which were later constrained into an assembly.

**Figure 4.** EGR valve model of Opel Astra 1.4 [6].

![Figure 4. EGR valve model of Opel Astra 1.4 [6].](image1)

**Figure 5.** EGR valve body flange.

**Figure 6.** EGR valve shaft.
The real design challenge was the valve body. It was divided into simple geometric bodies which were later assembled using the “Unite” command on the valve body flange (figure 5). All geometric bodies were created using the “Extrude” command. In the same way, the valve shaft was created, having the open position, thus allowing the passage of the flue gases inside the engine, where the combustion reactions took place (figure 6).

![Figure 7. Circuits of coolant.](image)

![Figure 8. Circuits of flue gases.](image)

After the creation of the geometric bodies, the circuits of the two fluids, the coolant (figure 7) and flue gases (figure 8) were created. The same “Extrude” command was used only in the areas through which the fluids pass, material was extracted using the “Subtract” option at the “Extrude” command. The material extractions left sharp edges and surfaces that were rounded using the “Edge Blend” and “Face Blend” commands.

The other parts of the valve, the electrical coil and the short pipe are two separate “.prt” files and were made with the same “Extrude” command. The assembly was completed. The body valve is the basic component on which the other parts are assembled using position constraints such as “Concentric”, “Align” and “Touch”.

Finally, using a “True Shading Editor” view (figure 9, 10), specific colours were defined for each part:
- the body valve the colour of an aluminium alloy;
- ebonite (black) or hard plastic connector;
- electrical coil covered with a thin steel sheet;
- short pipe aluminium alloy

![Figure 9. EGR valve, CAD assembly.](image)
4. The Fluent flow analysis
After making the 3D assembly, it was imported into Ansys to model the flow of fluids with different states of aggregation which are:

- the exhaust gases that will enter in small quantity in the engine’s combustion space;
- the rest of the flue gas is removed from the engine through the exhaust;
- the coolant in order to reduce the overheating of the body valve and to protect the electrical coil that acts to open or close the valve;

Prior to the mesh discretization operation, it is important to rename the fluid-solid separation surfaces for both flue gases and coolant. For the modelling operation, carbon dioxide (CO₂) was used as exhaust gas and water was used for the coolant. The solid-liquid separation surfaces are also renamed, mentioning that for the body valve and for the short pipe, an aluminium-based alloy was used as material.
After renaming the separation surfaces, it is good for each solid component in the 3D assembly to be defined as domains using the “Body Element” option in the toolbar.

![Figure 12. The exhaust gas meshed domain.](image)

With the "Fill" option, the spaces occupied by the coolant and the exhaust gas were well defined (figures 11, 12). As with solid bodies, the volumes occupied by fluids were named after which, the discretization operations were performed. It is recommended that when applying discretization operations on fluid volumes to apply the “Inflation” operation to the fluid-solid separation surfaces, where five successive layers of fluid with a thickness of 1 mm between them have been created. This can be seen in the figures 11 and 12. After the discretization operation with finite volumes, 176614 nodes and 603956 microvolumes were obtained for the field occupied by the flue gases, and for the field occupied by the cooling liquid 130241 nodes and 482182 microvolumes.

Another operation that must be taken into account in the operation of discretization with finite volumes of the fluid domains is that on the “inlet” and “outlet” surfaces to apply a dimensioning of the “Face Sizing” type surfaces to which “Element Size” has the value 1 mm.

The finite element discretization operations of parts of the valve were performed differently from the volumes occupied by the fluids. The assembly consisting of the body valve and the short pipe will contain after meshed operation 30069 nodes and 94155 elements for the short pipe and 411111 nodes and 2158618 elements (figure 13).

![Figure 13. The body valve meshed domain.](image)
Then I entered the Setup menu from Fluent, a “Check Mesh” is made from where a “Quality Report” is obtained and here a parameter called “Orthogonal Quality” (range from 0 to 1) is deduced. If the value of this parameter is closer to zero then the quality of the meshed zone is poor. If its value is less than 0.01 then the mesh operation must be resumed. In our article, for this parameter the value 0.02 was obtained. In our case, the explanation why this parameter has such a small value is primarily due to the complexity of the 3D model.

Ansys Fluent was used to model the flow of fluids in different states of aggregation (flue gases and coolant). From various sources [7] it is specified that the valve will not open at idle or when the engine is cold. The valve will open periodically and not when you press the accelerator pedal to the floor but when driving the car at low and medium loads. When you do not press the accelerator pedal or when you press fully, the EGR valve will not open, but it is possible to open between these marks if the engine is warm enough. The EGR valve has a sensor that will decide when the valve opens and the driver will not have to do anything.

Unfortunately, EGR breaks down and this is a problem related to the operation of cars. These valves work directly with the engine pollutants, the gases are cooled by a special system before passing through the EGR valve. An expected flue gas temperature before entering the EGR is 130°C, the temperature that was taken as a boundary condition for modelling the flue gas flow from this article. It is specified that one of the causes of failure of this valve is that of driving in the city for a long time. The common fault of these valves is clogging the valve and locking it in a certain position and this will affect the proper operation of the engine in the sense that the engine will emit a lot of smoke and will not respond to acceleration as in its good times.

As it is specified in the technical book of the car [5] the flue gases will be recirculated in small quantities. We considered as boundary conditions for the flue gases the following:

- for the flue gases entering the valve we set for pressure inlet the value 49000 Pa = 0.5 bars;
- as flue gases we set the carbon dioxide CO₂ which has the inlet temperature in the valve \( T=130^\circ C \);
- as can be seen in the design of the valve body (figure 13), the flue gas circuit forks into two circuits, one of them passes through the valve on a short path, and the other path is longer and passes through the hole left free by the valve opening;
- at the outlet of the flue gas towards the exhaust, a pressure outlet type condition with a value of 29400 Pa = 0.3 bars was set, registering a small pressure loss because the circuit of these gases to the outlet of the valve is short without losing much of the heat that was set at \( T=120^\circ C \);

![Temperature Contour](image.png)

**Figure 14.** The temperatures volumes of coolant and flue gases
the flue gases used for recirculation will enter the combustion space of the engine once the valve is opened. For these, a pressure outlet type boundary condition with the value 19600 Pa = 0.2 bar was used;

the modelling of the flow of these gases presented in this article was made in the conditions in which it is considered that the valve is already open and the gases enter in small quantities back into the engine. The circuit of these gases is longer than that of the gases coming out towards the exhaust (figure 14). The orifice through which the gases come out (diameter = 6 mm) after opening the valve makes the gas blanket to be thinned so that its pressure increases easily and the gas cooling becomes easier (figure 16). The temperature at the exit of these gases from the body valve and at the return to the engine was set at T=90°C.

for the coolant entering the valve, the value 39200 Pa = 0.4 bar was set for the pressure inlet;
the coolant circuit is long enough and covers almost all areas of the valve (figures 14);
I set as coolant the water that at the entrance to the valve has a temperature of T=30°C because it does not come directly from the radiator, it goes through a longer circuit and it is possible to register a slight increase in it.
when the water comes out of the body valve I set the pressure outlet with the value 37240 Pa = 0.38 bar, a slight pressure drop because the water circuit inside the valve is without obstacles and the temperature is T=96°C.

![Figure 15. The temperature contours of body valve and fluids](image1)

![Figure 16. The section planes: a – flue gases pressure; b – flue gases temperature.](image2)
5. Conclusions
The 3D assembly made with NX Siemens was made with all dimensions measured on the real EGR valve from an Opel Astra 1.4. In the process of designing the EGR valve, the real challenge was to make the valve body due to its complexity.

For the flow of fluids, information presented in various sources such as Service and Repair Manual as well as other sources that were mentioned in the article were used.

In the first part of the paper were presented some researches that have shown that at low degrees of flue gas recirculation it is possible to achieve a significant reduction of NOx-containing pollutants.

At the discretization processes with finite volumes of fluids a series of difficulties were encountered because the mesh operation had to be performed with great caution because in the "Run Calculation" operation we often had warnings such as "Reverse flow in faces" which generated fall.

The following conclusions can be drawn in modelling fluid flow:

- the coolant does not take much of the flue gas temperature, its role being more to maintain a proper temperature of the body valve (figure 15) that does not adversely affect the operation of the coil and the sensor that opens the valve;
- the flue gases entering the EGR valves passing through the short circuit to the exhaust will not be consistently cooled;
- the flue gases entering through the open hole of the valve will form some thin gas beds which will cool faster (figure 16, b) after which they will enter the engine.

At the initial “Run Calculation” operation, a “Number of Iteration” equal to 20 was chosen and it was followed if there is a convergence of solutions, after which we moved to a “Number of Iteration” of 5000.

6. References
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