Int j simul model 22 (2023) 4, 679-689
Original scientific paper

SIMULATION MODEL OF VEHICLE EMISSION REDUCTION EXHAUST SYSTEM

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Abstract
Constantly tightening vehicle emission standards leads to the creation of new technologies for reducing the content of toxic substances in exhaust gases while maintaining the highest possible engine performance. At the moment, however, it is clear that with regard to future emission standards, despite the technologically highly refined system of catalytic converters, the reduction of emissions with the help of catalytic converters alone will be insufficient. That is why a variable exhaust manifold/system was developed and patented, which has a significant impact on the reduction of vehicle emissions. This innovation enables three working modes of the engine, depending on the demand and output power requirements. The presented article presents the complex architecture of the proposed system, including the description and simulation of individual operating modes. The first working mode is the most ecological and economical mode, but it has a relatively lower performance. The second working mode is characterized by the production of higher power, and the third mode can be used at high engine loads.
(Received in August 2023, accepted in September 2023. This paper was with the authors 1 week for 2 revisions.)

Key Words: Simulation Model, Variable Exhaust System, Emission Reduction, Vehicle

1. INTRODUCTION

One of the most important components in modern-day engines is the exhaust manifold, which utilizes the turbocharger needed for forced induction. Forced induction is an inseparable technology of small combustion engines due to its possibility to significantly increase the power output of the engine. The exhaust manifold architecture is dependent on many parameters such as backpressure, velocity of exhaust gas, turbulence of exhaust gas, etc. Some of the most important parameters that are monitored during the design are backpressure and exhaust gas velocity at the outlet. The exhaust backpressure has the main role in terms of engine performance and economy. The higher the exhaust backpressure is lower the engine performance as well as bad fuel economy. For example, performance vehicles use exhaust manifolds/exhaust systems with the lowest backpressure to achieve maximum power of the engine. The exhaust gas velocity at the outlet should be as high as possible to achieve good thermal efficiency and mechanical efficiency. The exhaust manifold collects gases produced during combustion in cylinders. In a multi-cylinder engine, the exhaust manifold collects exhaust gases from different cylinders which flow to the single pipe of the vehicle´s exhaust system or into the turbocharger and then to the exhaust system. Modern engines also utilize a cylinder deactivation system to which the exhaust manifold design must correspond. Exhaust manifolds are usually made of cast iron, but stainless steel is also used mainly in racing applications where the operating temperature of the exhaust manifold is much higher than in urban use. Many CFD exhaust manifold analyses have been done by many scientists who observed the parameters of many designs to improve the exhaust manifold design. These analyses helped to improve not only the engine performance but also the engine efficiency and fuel economy of the internal combustion engine [1-6].

https://doi.org/10.2507/IJSIMM22-4-675

2. METHODOLOGY

2.1 Exhaust manifold/system design for cylinder deactivation technology

The exhaust system was designed using CAD (Computer Aided Design) and analysed in CFD software. The CAD model design is based on research related to exhaust manifolds/systems of modern engines with cylinder deactivation systems but also at the basis of motorsport research to improve engine performance [7, 8].

2.2 Exhaust manifold/system CAD design and function

The designed exhaust system (Fig. 1) utilizes two different technologies. The cylinder deactivation technology connected with forced induction deactivation [9-11] should reduce fuel consumption of internal combustion engines in urban areas while ensuring sufficient engine power in difficult conditions like overtaking, driving uphill, or towing.

Figure 1: Exhaust manifold/system design.

The dual exhaust manifold system for optimization of the combustion process consists of an inlet air pipe mouthed into the combustion engine connected by means of an air reservoir with a high-pressure air pipe opening radially into the driven part of the turbocompressor, which is also axially connected to a low-pressure air pipe (Fig. 2). At the same time, it consists of an active exhaust pipe with a valve, a passive exhaust pipe with a valve, a connecting pipe with a valve, an additional catalytic converter, a discharge exhaust pipe with a clap, a mixing pipe, and a main catalytic converter. The essence of the invention is that the active exhaust pipe with a valve connected to the odd exhaust channels of the engine is opened to the additional catalyst, which is connected to the main catalyst by a mixing pipe, and the passive exhaust pipe with a valve connected to the even exhaust channels of the engine is opened radially to the drive part of the turbocompressor, the axial outlet of which is connected to the mixing pipe by means of a discharge exhaust pipe with a valve, and at the same time the active exhaust pipe with a valve is connected behind the engine to a passive exhaust pipe with a valve by a connecting pipe with a valve. The overall design enables the optimization of the combustion process and the reduction of emissions depending on the immediate operating load of the engine, by providing the possibility for the engine to work in different modes.

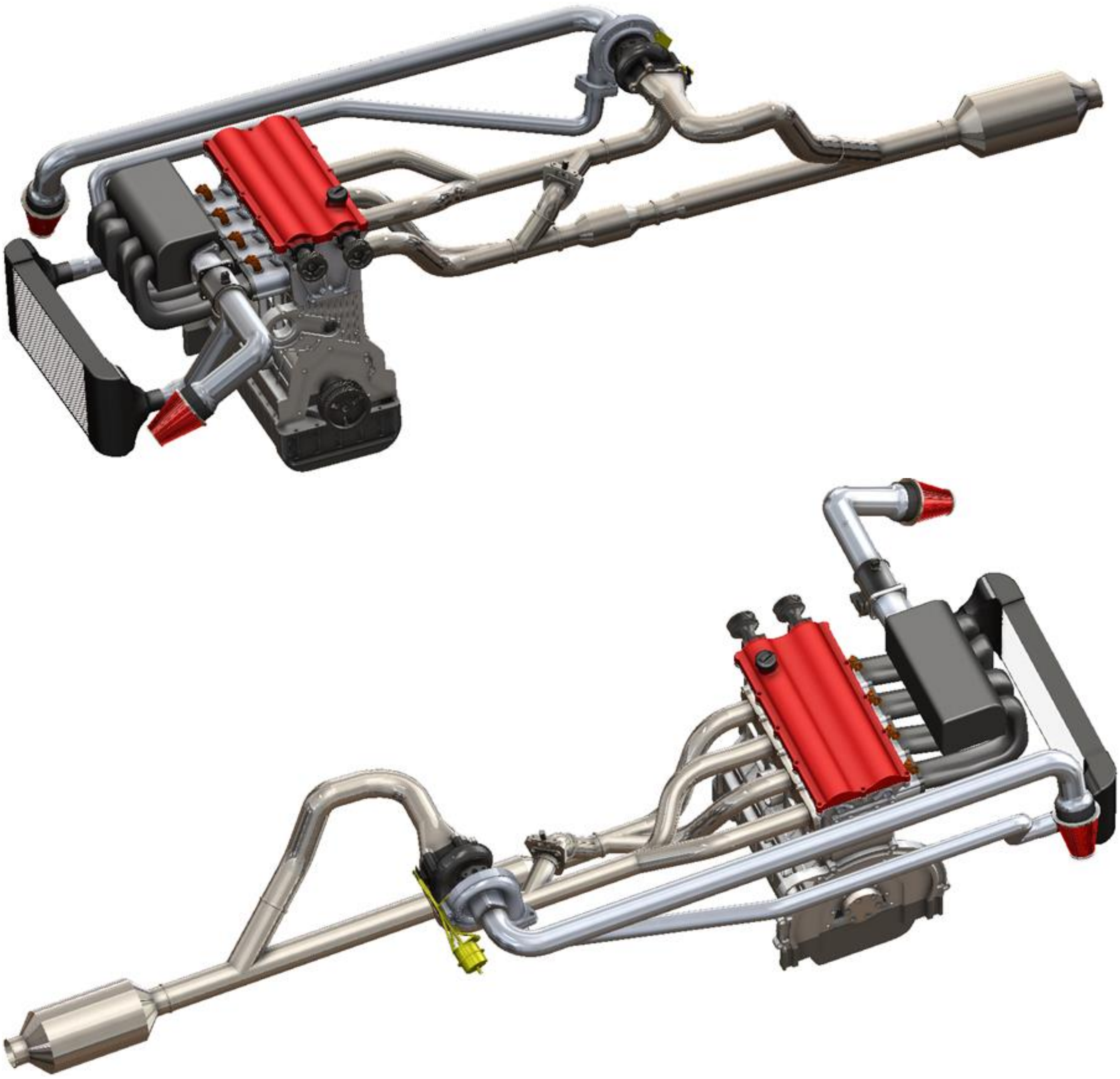

Figure 2: Exhaust manifold/system connected to four-cylinder internal combustion engine.

A dual exhaust manifold system for optimization of the combustion process according to Fig. 3 was applied to an internal combustion engine, where it forms part of the engine system to ensure higher efficiency in the use of a homogeneous fuel mixture. The dual exhaust manifold system for the optimization of the combustion process consists of an inlet air pipe 1 opening into the combustion engine 2 connected by means of an air reservoir 3 with a high-pressure air pipe 4 opening radially into the driven part of the turbocompressor 5, which is also axially connected to a low-pressure air pipe 6, from active exhaust pipe with valve 7, passive exhaust pipe with valve 8, connecting pipe with valve 9, additional catalytic converter 10, discharge exhaust pipe with valve 11, mixing pipe 12 and main catalytic converter 13, characterized in that the active exhaust pipe with valve 7 connected with the odd-numbered exhaust channels of the engine 2 is mouthed into the additional catalytic converter 10, which is connected to the main catalytic converter 13 by a mixing pipe 12, and the passive exhaust pipe with a valve 8 connected to the even-numbered exhaust channels of the engine 2 is mouthed radially into the drive part of the turbocompressor 5, the axial output of which is connected to the mixing pipe 12 by means of a discharge exhaust pipe with a flap 11, and at the same time the active exhaust pipe with a valve 7 is connected behind the engine 2 to a passive exhaust pipe with a flap 8 through a connecting pipe with a valve 9.

In the first working mode, the passive exhaust pipe with valve 8, the connecting pipe with valve 9, and the discharge exhaust pipe with valve 11 are closed. The exhaust gases flow through the active exhaust pipe with valve 7 connected to the non-vapour exhaust channels of engine 2 to the additional catalytic converter 10 and further through the mixing pipe 12 to the main catalytic converter 13. This is the most ecological and economical mode, but it has relatively lower performance. The second operating mode is characterized by a closed active exhaust pipe with valve 7 and a passive exhaust pipe with valve 8. The exhaust gases flow through the open part of the active exhaust pipe with valve 7 connected to the odd exhaust channels of engine 2 and a connecting pipe with valve 9 radially into the drive part of the turbocompressor 5, then through the axial outlet using the discharge exhaust pipe with valve 11 to the mixing pipe 12 and the main catalyst 13.

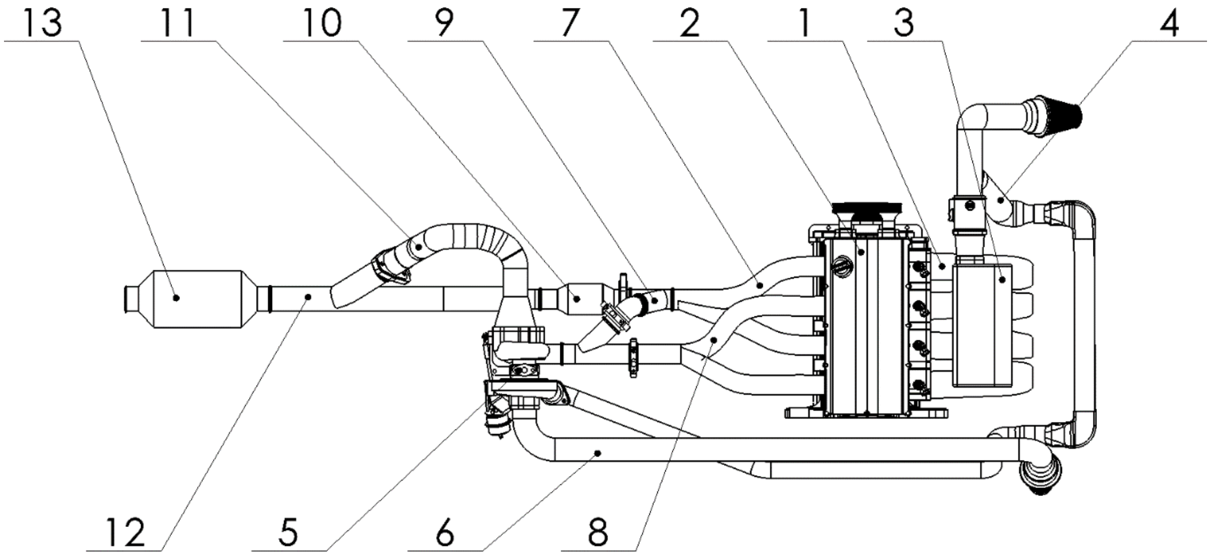

Figure 3: Exhaust manifold/system connected to four-cylinder internal combustion engine diagram.

This is a more powerful system. The third working mode is characterized by the closing of the active exhaust pipe with valve 7. The engine works with the use of all cylinders. The exhaust gases flow through the open part of the active exhaust pipe with valve 7 connected to the odd exhaust channels of engine 2 and the connecting pipe with valve 9 as well as through the passive exhaust pipe with valve 8 radially to the driving part of the turbocompressor 5, then through the axial outlet by means of the discharge exhaust pipe with the valve 11 into the mixing pipe 12 and the main catalytic converter 1. This mode can be used at high engine loads 2 [12-14].

2.3 Simulation results

The exhaust manifold design was tested in the simulation software Ansys. Results showed that the design could be used as the basis for testing in real life [15, 16].

The system will work in three power regimes, which first will be a naturally aspirating engine with the lowest performance while producing the lowest emissions. The exhaust gas velocity variation along the exhaust system is shown in Fig. 4.

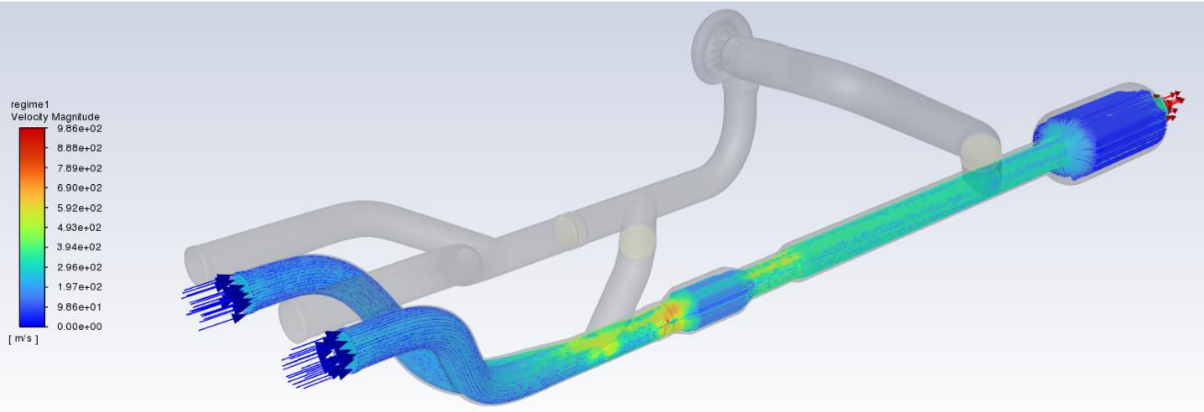

Figure 4: Exhaust gas velocity.

The exhaust gas velocity increases at the main catalytic converter and decreases at the secondary catalytic converter. Velocity reduction is predicted since the secondary catalytic converter can take a high volume of entering gas. The turbulence that occurs inside the piping is shown in Fig. 5.

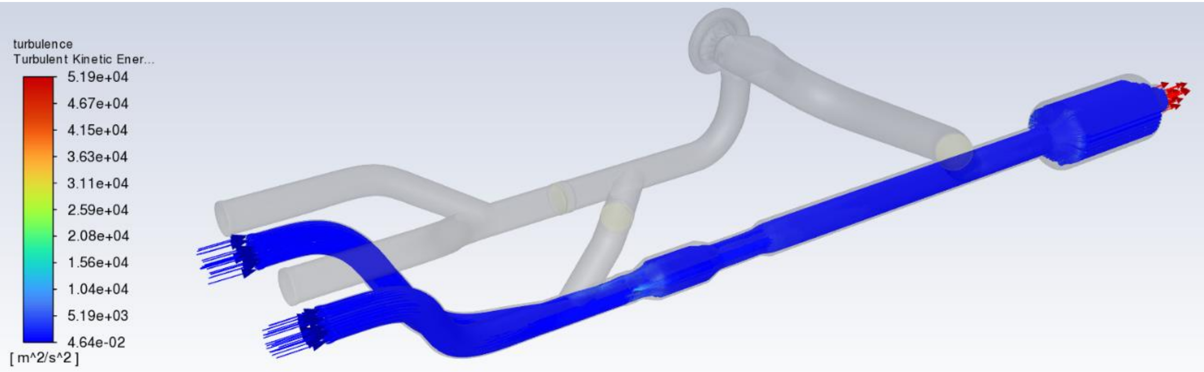

Figure 5: Exhaust gas turbulence.

As shown in Fig. 5 the turbulence in the exhaust is low which means good exhaust gas removal from the system. The pressure inside the system was analysed too and can be seen in Fig. 6.

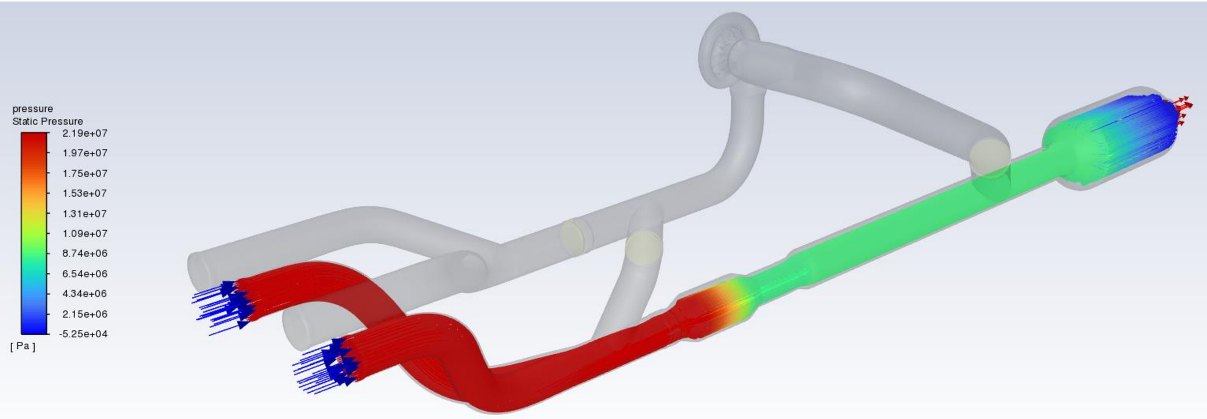

Figure 6: Pressure inside the exhaust system.

The gas pressure drop after the main catalytic converter was predicted as well as after the secondary catalytic converter since there is porous material that cleans exhaust gases from toxic substances [17]. The prediction was confirmed by the simulation. For better monitoring of pressure, the pressure chart is shown in Fig. 7.

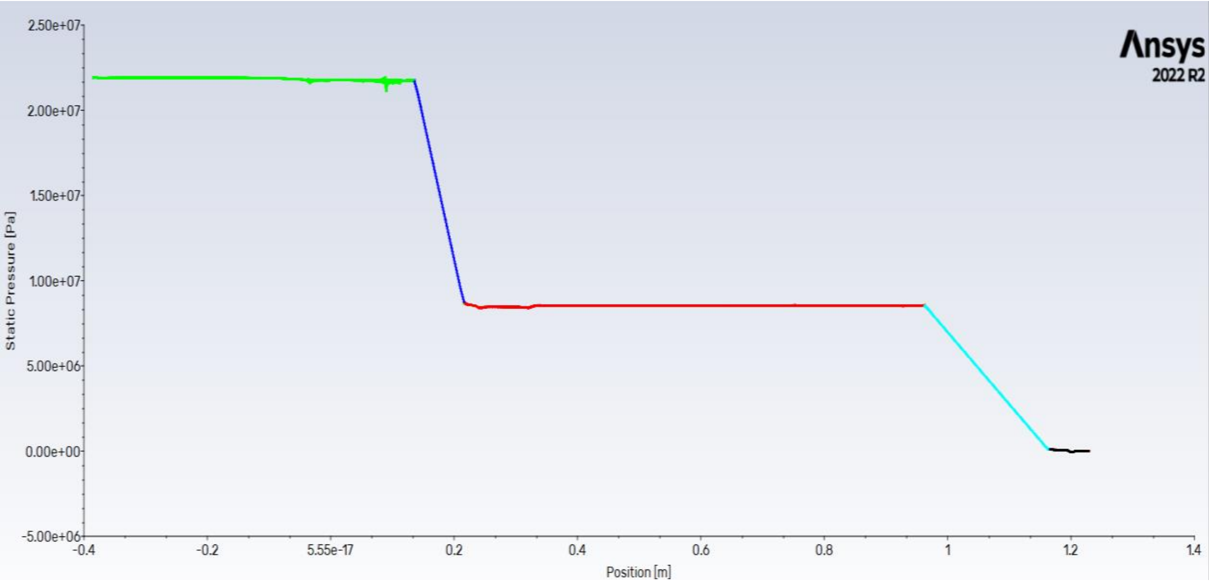

Figure 7: Gas pressure chart.

As soon as the simulation of the first regime was done, regime two underwent simulation showing velocity, turbulence, and pressure. The second regime works with two cylinders where the exhaust gas is driven inside the turbocharger and then to the secondary catalytic while the primary catalytic converter is omitted. This second regime is used when the engine is at operating temperature and the secondary catalytic converter reaches operation temperature. Exhaust gas velocity variation is shown in Fig. 8.

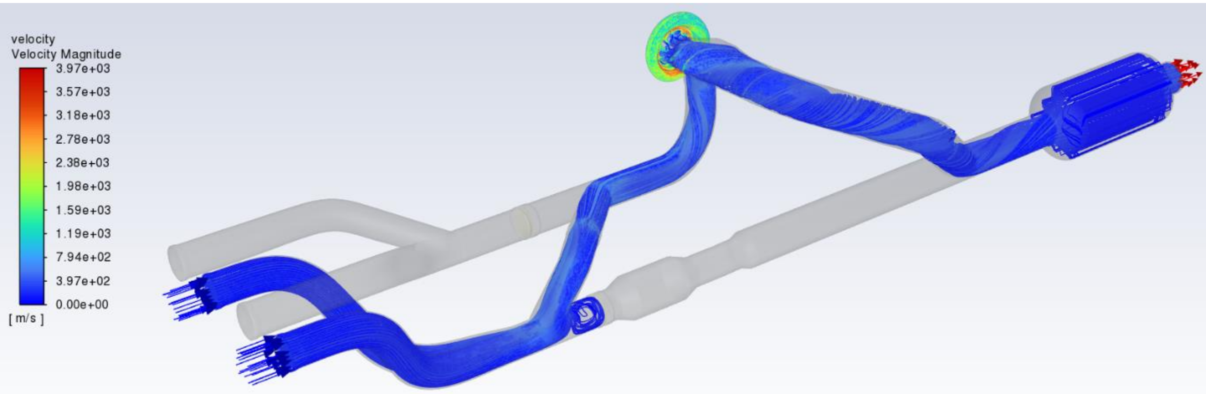

Figure 8: Gas velocity inside the system.

The velocity increases in the area of the turbocharger and decreases once it exists the turbine wheel of the turbocharger. The second observed parameter was exhaust gas turbulence shown in Fig. 9.

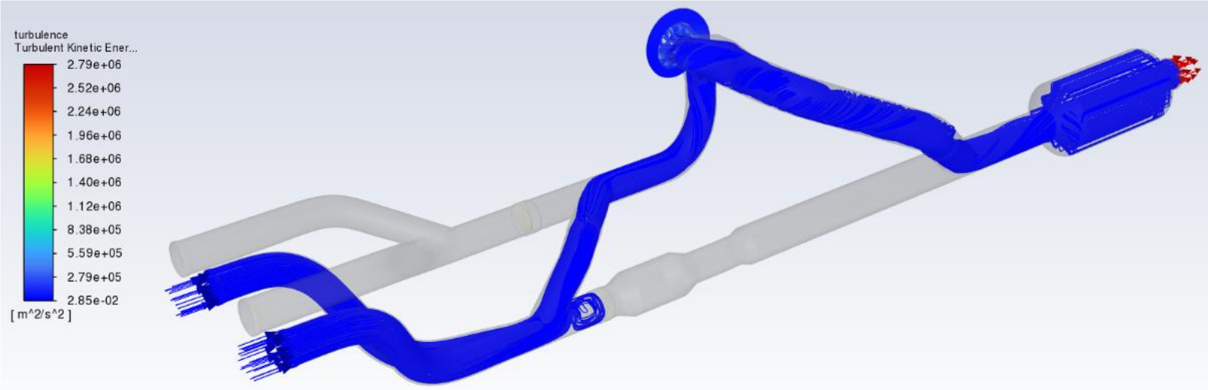

Figure 9: Turbulence variation inside the exhaust system.

As well as the first regime, the turbulence is kept at low values. The next parameter is the pressure shown in Fig. 10.

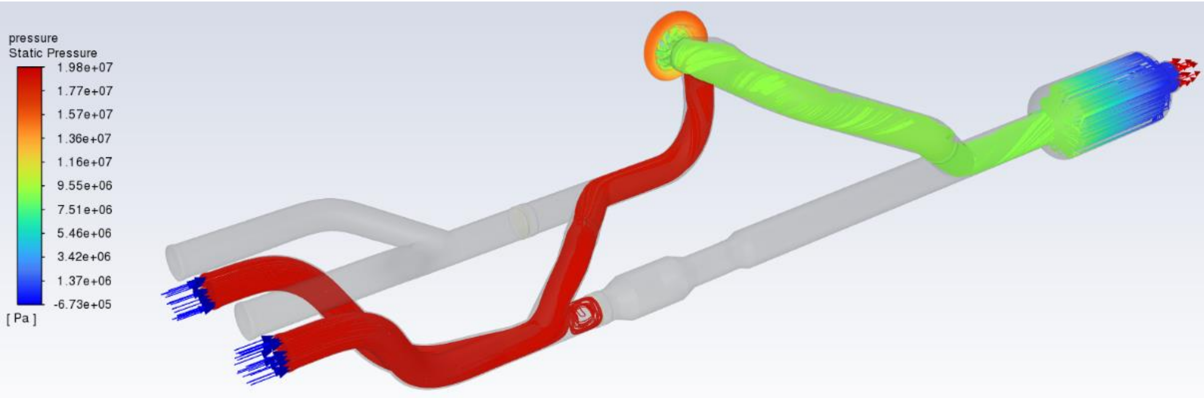

Figure 10: Pressure variation in the exhaust system.

In comparison to the first regime, the pressure drop occurs after the turbocharger and not at the area where the primary catalytic converter sits. Also, a significant pressure drop occurs in the second catalytic converter as predicted during the design. For a better understanding of pressure values, the pressure chart inside the exhaust system is shown in Fig. 11.

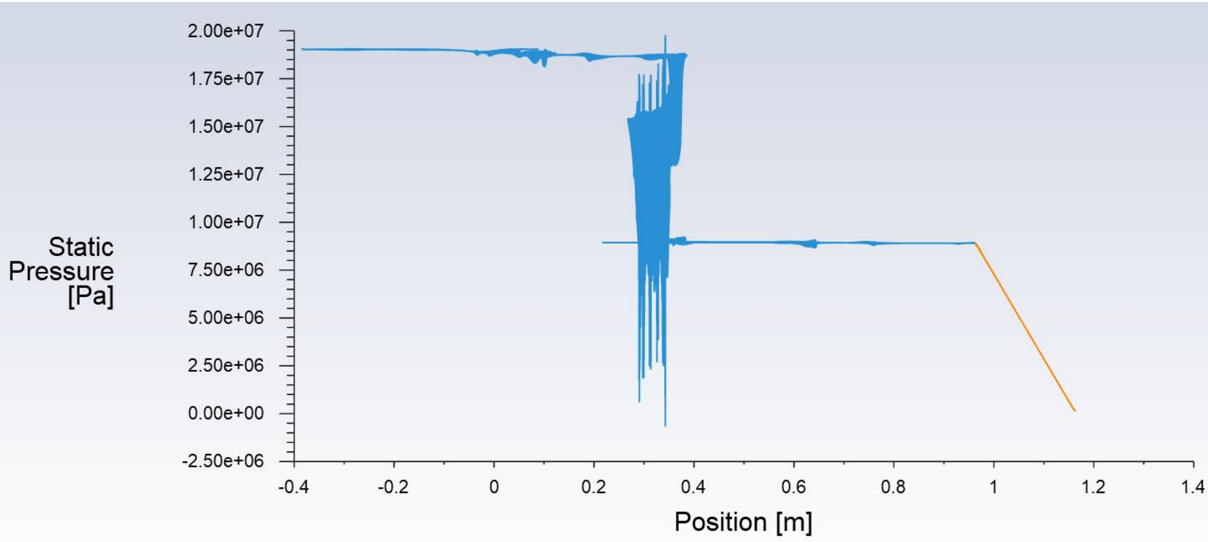

Figure 11: Exhaust system pressure chart.

The third regime works as four-cylinder engine when the exhaust gas is driven into the turbocharger and from the turbocharger to the secondary catalytic converter while the primary catalytic converter is left out. This regime counts with the engine warmed up to operation temperature as well as the secondary catalytic converter warmed to temperature when it is able to eliminate toxic matter in the exhaust gas. The performance of the engine is as high as possible in this regime too. As in previous regimes, velocity, turbulence, and pressure are analysed in simulation software. The velocity variation in the exhaust system is shown in Fig. 12.

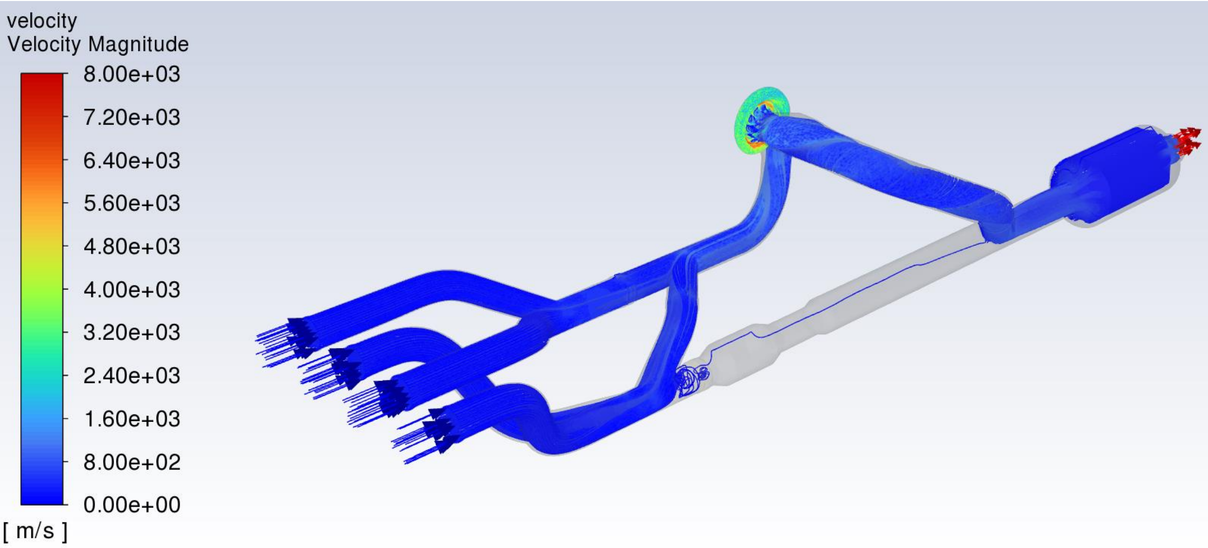

Figure 12: Gas velocity variation in the exhaust system.

The results show velocity increase at the region of the turbocharger due to rotation of the turbine wheel. Some gas returns to the primary catalytic converter which can be a problem of simulation or a problem of design, however, this fact does not greatly affect the system functioning. Another monitored parameter was the turbulence shown in Fig. 13.

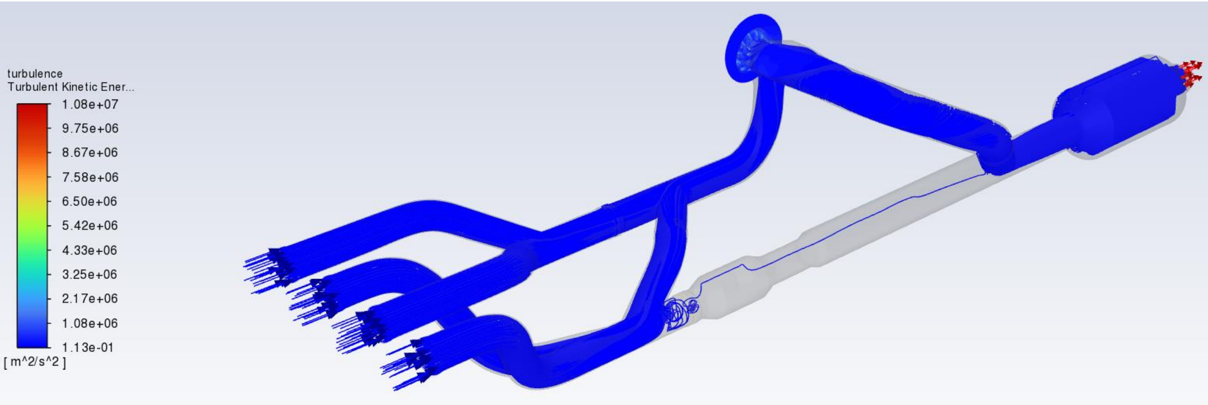

Figure 13: Turbulence variation inside the exhaust system.

As in the previous case, there is very little turbulence inside the exhaust manifold/system. The pressure inside the system based on simulation is shown in Fig. 14.

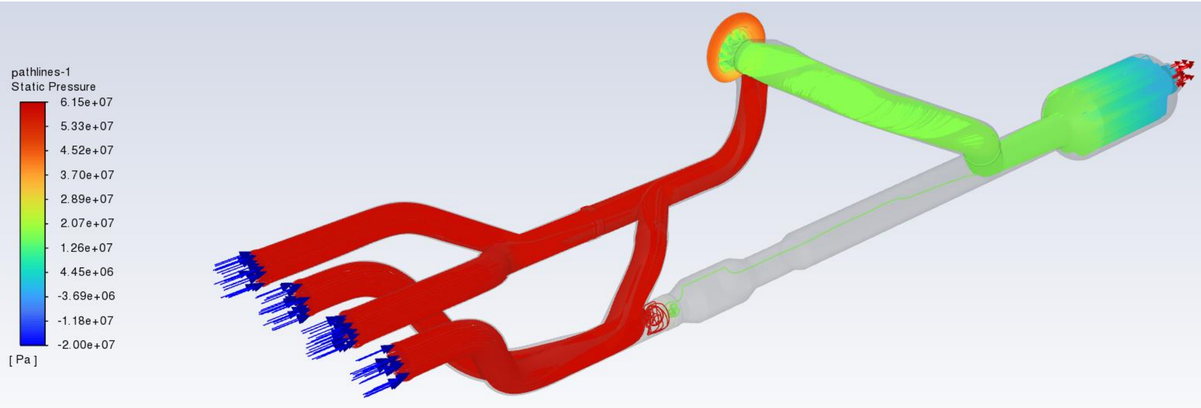

Figure 14: Pressure variation in the exhaust system.

The pressure inside the exhaust system is like the system operating in the second regime, which means that the pressure decreases after the turbocharger and at the outlet of the secondary catalytic converter. For better pressure values evaluations the pressure chart is shown in Fig. 15.

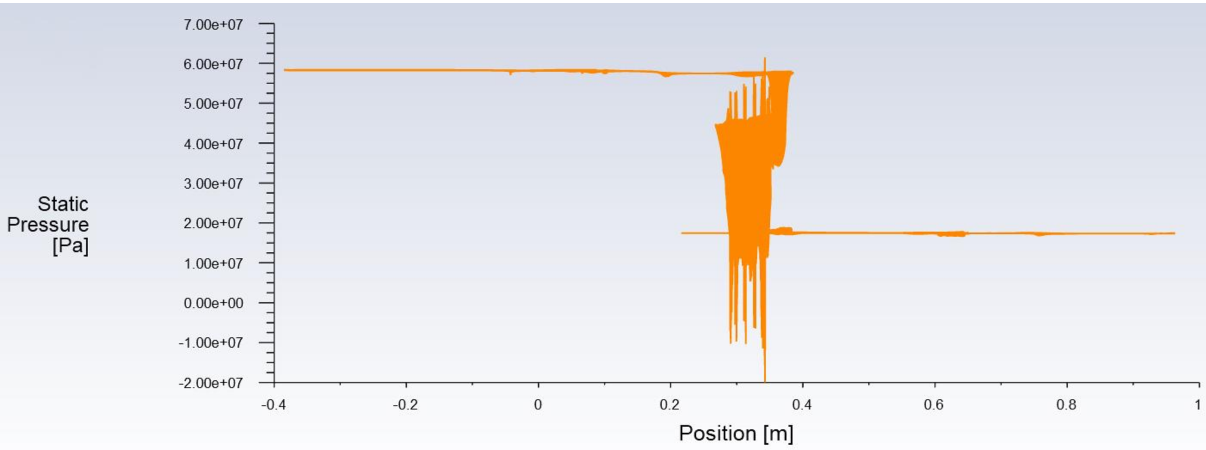

Figure 15: Exhaust system pressure chart.

Table I contains a summary of the results of all simulations. The individual regimes are defined in detail together with the expected operating parameters. The first regime is the most ecological since the engine operates only in two-cylinder naturally aspirated mode, with usage of two catalytic converters. The maximum pressure is slightly higher in comparison to second regime, which can be caused by the restrictive primary catalytic converter. The exhaust gas velocity is the lowest with minimal turbulence. Analysis shows that this regime can be used for ecological driving with low fuel combustion at long sections with constant speed or urban driving.

Table I: Review of simulation models.

Regime	**Number of cylinders**	**Catalytic converter**	**Turbocharger**	**Maximum pressure till** [Pa]	**Maximum velocity** [m/s]	**Maximum turbulence** [m^2/s^2]
1	2	2	No	2.19 e+07	690	2.08 e+04
2	2	1	Yes	1.98 e+07	3,180	8.38 e+05
3	4	1	Yes	6.15 e+07	6,400	3.25 e+06

When the primary catalytic converter is disconnected and the turbocharger is connected, the maximum pressure drops due to the lower restriction of the turbine wheel of the turbocharger.

The exhaust gas velocity value increases as well as maximum turbulence. The engine emissions as well as fuel combustion with this regime rise due to the higher power of the engine. This regime is suitable for moderate engine loads. The third regime unlocks the full potential of the engine when the maximum engine power is generated with the usage of four cylinders and a turbocharger. The maximum pressure is therefore the highest from all regimes as well as the velocity and turbulence of exhaust gases. The characteristics of this regime are maximum power, increased emissions, and fuel consumption, which can be used in specific demands with maximum engine loads.

3. CONCLUSION

This paper shows the design of the exhaust manifold/system which works with two different technologies, cylinder deactivation and forced induction deactivation. The designed system underwent thorough flow simulation in Ansys software, which provided data on velocity, turbulence, and pressure inside the system when gas flows through the exhaust. According to the results, a prototype of this exhaust manifold can be made and tested in real life however, some changes and new simulations will be necessary due to the dimensions of the vehicle´s engine compartment. The overall concept is suitably designed, it is the subject of patent proceedings and in the next phase, the system will be manufactured and tested on a real engine together with emission analyses.

The future research plans is focused on further research and development of innovations determined for a more efficient utilisation of the renewable energy sources with regard to the planned emission limits. Our attention will be focused mainly on increasing of the efficiency during combustion of the fuels containing bio-components.

ACKNOWLEDGEMENT

This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-19-0328. The article was written in the framework of Grant Projects: VEGA 1/0318/21 "Research and development of innovations for more efficient utilization of renewable energy sources and for reduction of the carbon footprint of vehicles" and KEGA 007TUKE-4/2023 "Transfer of innovations and advanced technologies, determined for more ecological and more efficient vehicle drive systems, into the educational process".

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