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The influence of biogas injector location on air-biogas mixture homogeneity in a dual-fuel compression-ignition engine

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This paper deals with the dual-fuel supply of a compression-ignition engine fuelled with diesel oil and biogas. The aim was to investigate the influence of the location of biogas injectors in the engine intake manifold on the selected characteristics of the air-biogas mixture introduced into the cylinders. A 3D scanning of geometrically complex elements was used as part of the development of a detailed 3D model of the engine intake system. A simulation of the fluid flow was performed for several variants of biogas injector location. The boundary conditions for the simulation were determined experimentally in the engine dynamometer test cell. The obtained results were analysed in terms of the homogeneity of the air-biogas mixture formed in the intake manifold. Finally, the optimal location of the injector was identified. The conclusions from the study provide guidance for the implementation of biogas injection solutions in compression-ignition engines operating in dual-fuel mode.

Key words: *dual-fuel engine, biogas, flow simulation, fuel injection, mixture homogeneity*

1. Introduction

The use of internal combustion engines (ICEs) has been a subject of fierce debate in recent decades. The prevailing trend is to gradually phase out the use of ICEs in both mobile and stationary applications. The reason behind it is mainly the negative impact of engines on environmental aspects, such as the emission of pollutants that endanger the health of living organisms and cause the global climate to be unstable [9]. Furthermore, the large-scale use of non-renewable natural resources for the production of petrol and diesel oil has become a growing issue [18]. In response to the above threats, various proposals have emerged to address the shortcomings of ICEs powered by conventional fuels.

In transportation, the solution has been sought in the widespread use of electric drives, which offer numerous advantages, including energy efficiency, lower maintenance requirements, ease of control, and reliability [7]. However, practical experience has proved that the rapid implementation of such a concept on a large scale is not feasible. Limited energy storage in batteries and the lack of developed infrastructure remain challenges [22]. While efforts to electrify vehicle and machine drive systems have not been abandoned and are still being continued, there is a trend of returning to the well-known and proven methods of energy conversion offered by ICEs, although with a certain change in the approach to fuels used.

Currently, many car manufacturers assume that the continued use of ICEs requires switching to alternative fuels [22]. Among the numerous possible options, biofuels, hydrogen, and synthetic fuel are most often considered. Their use allows for maintaining the performance of ICEs at a similar level to current ones based on fossil fuels, but with significantly reduced environmental impact.

This paper focuses on biogas application in dual-fuel compression-ignition engines. This kind of alternative fuel has some favorable properties. Above all, biogas is renewable and can be produced from biomass of various origins, including waste [2]. The use of biogas reduces greenhouse gas emissions [16]. It is also a cost-effective solution, especially in rural areas, where it allows for the management of agricultural waste and the production of clean energy. On the other hand, raw biogas is not suitable for direct powering of combustion engines as it naturally contains only 40–60% of methane (CH_4), the only energy source, and the remaining substances, among others hydrogen sulfide (H_2S), water, siloxanes (silicon and oxygen compounds) and carbon dioxide (CO_2), are not combustible [8]. Purifying biogas to biomethane quality is a well-established technology [6], but it is associated with high energy expenditure, especially in terms of CO_2 removal. This prompts the search for areas of application of 'pre-purified' biogas, containing only CH_4 and CO_2. Although this solution has been successfully used for years in stationary engines of electricity generators operated in biogas plants, it raises certain technical challenges in relation to vehicle applications.

Another technical issue is the combustion system of biogas-powered ICEs. It has gained significant attention in scientific literature, particularly in practical publications. [23]. The most convenient way is to apply biogas to a spark-ignition ICE, which is the dominant method in stationary electric generating units [17]. Biogas application in a compression-ignition ICE is more challenging. Such an engine can operate in two modes: single-fuel or dual-fuel. In single-fuel mode, it uses only biogas, while in dual-fuel mode, it utilizes both diesel and biogas. Operating in single-fuel mode requires specific modifications to the engine, such as lowering the compression ratio and incorporating an ignition system similar to that of spark-ignition engines [5]. For simpler engines, these modifications are relatively easy to implement and do not significantly increase costs [19]. Conversely, compression-ignition engines operating in dual-fuel mode use diesel oil to initiate combustion through auto-ignition, which subsequently ignites the biogas-air mixture. In this case, it is necessary to add a separate biogas supply system and change the engine control algorithms [15].

Numerous research works have been carried out to investigate the performance of dual-fuel compression-ignition ICEs under all possible operating conditions, static and dynamic.

Matuszewska et al. [14] examined the emissions of exhaust gas components from a compression-ignition ICE that was converted for dual-fuel operation using diesel oil and biogas composed mainly of CO_2 and CH_4 with various proportions. The engine originated from an agricultural tractor, featuring four cylinders and an original diesel oil supply system with a distributor injection pump. The dual-fuel biogas conversion was accomplished without the need for complicated construction or regulatory adjustments. The dynamometer test results showed that compared to running solely on diesel oil, the dual-fuel system resulted in higher concentrations of hydrocarbons (HC) and carbon oxide (CO) and lower concentrations of particulate matter (PM) in exhaust gases. The level of emission of particular components depended on the biogas composition used. Jagadish and Gumtapure [11] studied a compression-ignition ICE fueled by dual-fuel diesel oil and biogas with increased methane content (88%). It was a single-cylinder, four-stroke engine with direct diesel oil injection into the cylinder and indirect biogas injection into the intake manifold. Selected operating parameters and pollutant emissions were compared between a dual-fuel engine (taking into account various doses of biogas) and an engine operating in single-fuel mode (powered by diesel oil only). While there were differences between the individual mixture variants with different biogas shares, some general trends could be identified when compared to a single-fuel diesel system. A reduction in emissions of nitrogen oxides (NO_x) and PM was observed, as well as an increase in emissions of CO and HC. More examples and generalization of research results can be found in the comprehensive review papers [8, 9].

Some researchers direct their efforts to investigate the phenomena related to biogas or biomethane injection and its optimization to improve ICE operating parameters.

Barik and Murugan [3] investigated the performance and emission characteristics of a compression-ignition engine operating in dual fuel mode with diesel oil injected directly into the cylinder and biogas inducted at varying flow rates to the intake manifold. Based on experimental findings, among the four biogas flow rates considered, a flow rate of 0.9 kg/h yielded the best engine performance along with the lowest emissions. In comparison to diesel-only operation, the dual fuel system demonstrated the highest peak cylinder pressure and a longer ignition delay. Notably, the dual fuel mode significantly reduced PM and nitric oxide (NO) emissions by about 49% and 39%, respectively.

Chandekar and Debnath [7] focused on the influence of ICE intake geometry on the mixing of methane-enriched biogas (90% CH_4) with air. They considered four intake systems with different injector configurations to optimize mixture homogeneity. The research was based on CFD simulation in ANSYS Fluent. The following quantities were compared between the considered configurations: pressure, velocity, turbulence kinetic energy, helicity, and mass fraction of CH_4. Particular attention was paid to determining the optimal ratio of the radius of the curvature of the manifold to the diameter of the manifold (R/D). The simulations showed that the best design was one with an R/D ratio of 1.75 and 2.

Adithya et al. [1] also conducted research on the optimization of the intake system of a dual-fuel compression ignition ICE, fueled with diesel oil and biogas. In contrast to the previously discussed paper [7], here the experiments were empirical, performed on a laboratory stand. The aim was to improve the volumetric efficiency of the ICE and to check the effect of the dual-fuel concept on pollutant emissions. Modification of the intake system, designed based on the Chrysler ram theory and Helmholtz resonator theory, allowed for increased ICE performance in single- and dual-fuel mode as well as reduced pollutant emissions.

Regarding the technical aspects of biogas-air mixture preparation, Bembenek et al. [2] noted that there is a lack of research on biogas injectors and decided to fill this gap. They selected five injectors available on the market and empirically tested their properties, such as contingent productivity, the linearity of operation, the injector response time, the resistance of the injector coil, the ability to maintain factory parameters, and the service life. On this basis, the researchers recommended the best injectors for use in both spark-ignition and compression-ignition ICEs.

A review of the scientific literature shows that numerous research results have been published on ICEs fueled with biogas, bio-CNG, and other biogas-based fuels. They mainly concern the basic operating parameters of the ICE, i.e. power, torque, fuel consumption, and pollutant emissions. However, there are disproportionately few papers devoted to the phenomena of biogas injection, which is a decisive factor for the formation of the fuel-air mixture and hence has a significant impact on the operating parameters of the ICE. Therefore, the aim of this paper was to investigate the influence of the location of biogas injectors in the ICE intake system on the selected characteristics of the air-biogas mixture introduced into the cylinders.

2. Experimental setup

The intake manifold considered in this study (Fig. 1) is a component of the intake system of the JCB 444 TA4i-81 I1 engine. Basic technical specification of the engine is given in Table 1. It was adapted to operate in a dual-fuel

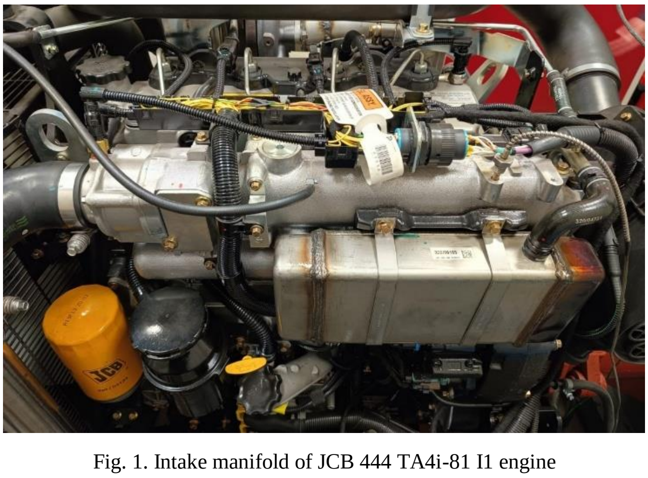

Fig. 1. Intake manifold of JCB 444 TA4i-81 I1 engine

system, with diesel oil as the primary fuel and biogas additionally fed to the air supplying the cylinders. The biogas injectors were initially located in the intake system, between the turbocharger and the intercooler. In this study, a new location of the injectors was proposed, i.e. in the intake manifold, closer to the engine cylinders.

Table 1. Main technical specifications of JCB 444 TA4i-81 I1 engine

Parameter	Data
Manufacturer	JCB
Type	444 TA4i-81 I1
General features	4-stroke, DOHC, compression ignition, turbocharged with intercooler
Emission compliance	US-EPA Tier 4i, EU Stage IIIB
Number and configuration of cylinders	4, in-line
Compression ratio	16.7
Bore/stroke [mm]	103/132
Displacement [cm^3]	4399
Rated power [kW@rpm]	81@200
Maximum torque [Nm@rpm]	516@ 1500
Fuel system	Direct injection, Common Rail
Cooling system	Liquid-cooled

3. Three-dimensional model of the intake manifold

In order to accurately reproduce the geometry of the internal spaces of the intake manifold, casting was made using molding silicone (Fig. 2). Due to the complex shape of the channels, the intake manifold was cut to remove the silicone castings. Silicon elements were scanned using the Micron3D Green Stereo scanner (Fig. 3), manufactured by SMARTTECH Ltd. [23]. Based on the obtained data, a 3D model of the intake manifold was developed (Fig. 4).

Fig. 2. Intake manifold filled with molding silicone

Fig. 3. Scanning of intake manifold castings with the SMARTTECH Micron3D Green Stereo scanner

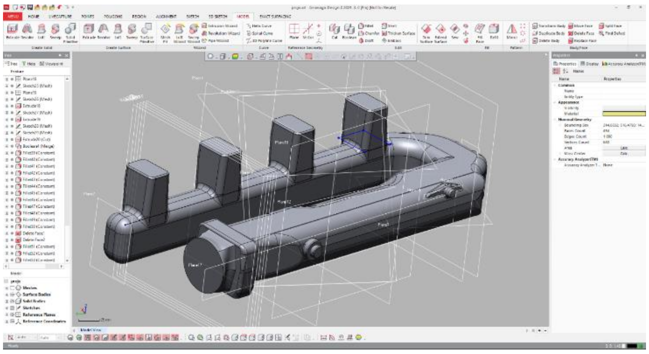

Fig. 4. 3D model of the interior of the intake manifold developed based on scanned data

4. Methodology of the research

The aim of CFD analysis was to find an optimal location for biogas injectors in the inlet manifold of a dual-fuel compression ignition engine. Additionally, one and four biogas injector concepts were studied. In the current research, ANSYS Fluent software was used for the simulations, which is a CFD solver of ANSYS Workbench 19.2 solution. At the beginning, the previously developed 3D model of the intake manifold was imported into the Design Modeler module of ANSYS Workbench 19.2 software. After some geometrical corrections, 3 models were developed for the needs of flow analysis. They are shown in Fig. 5–7. Numbers in red correspond to the cylinder numbers. Model 1 shown in Fig. 5 has only 1 biogas inlet (1 injector concept) located at the entrance to the manifold. Model 2 (Fig. 6) and model 3 (Fig. 7) have four biogas inlets (4-injector concept) gathered in series and located at various distances from the manifold's outlet. According to preliminary assumptions, a four-injector solution would allow for an increase in the air-biogas homogeneity formation rate compared to the 1-injector case.

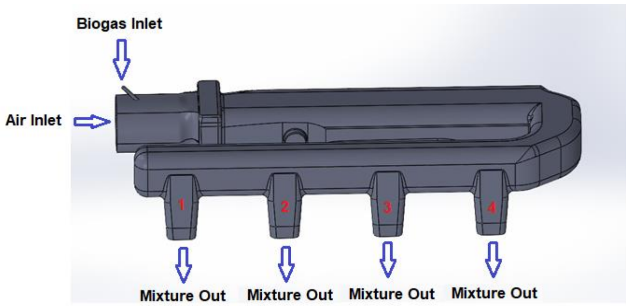

Fig. 5. 3D model of intake manifold with one biogas inlet (model 1)

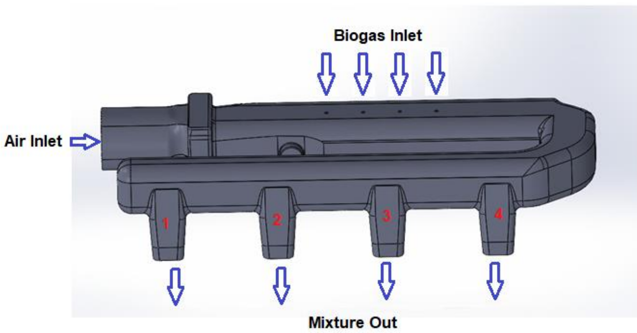

Fig. 6. 3D model of intake manifold with 4 biogas inlet (model 2)

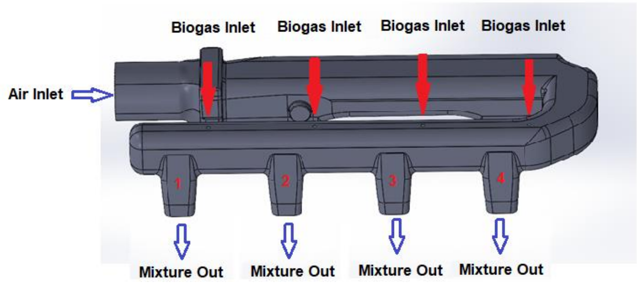

Fig. 7. 3D model of intake manifold with 4 biogas inlet (model 3)

To discretize the models, ANSYS Mesher was used. Meshed models are shown in Fig. 8 to Fig. 10. Meshing was done with the standard 5-layer inflation. There were 1553795 elements and 297199 nodes generated for model 1, 1567226 elements and 298941 nodes for model 2, and 1590822 elements and 303268 nodes for model 3. Other common characteristic dimensions of the mesh are as follows: target skewness 0.9 (default), medium smoothing, inflation with smooth transition, and transition ratio 0.272, growth rate 1.2; mesh sizing with capture curvature.

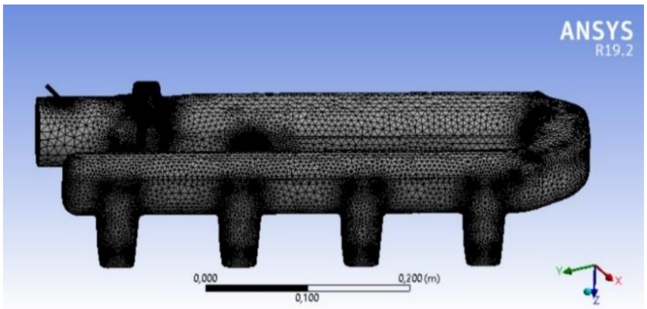

Fig. 8. Meshed model of intake manifold with one biogas inlet (model 1)

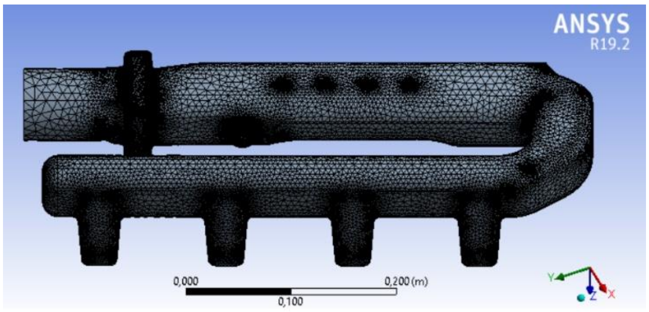

Fig. 9. Meshed model of intake manifold with 4 biogas inlets (model 2)

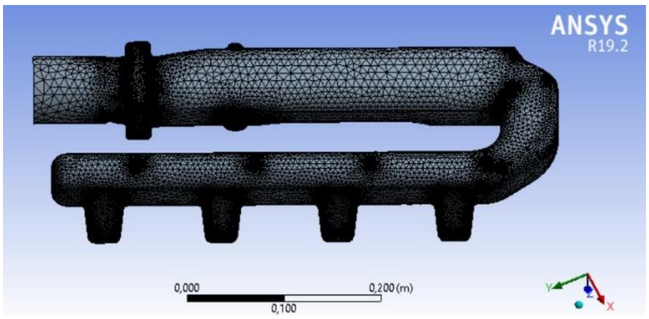

Fig. 10. Meshed model of intake manifold with 4 biogas inlets (model 3)

The Navier–Stokes equations and the species transport equation were applied for flow simulations. The energy equation was also used. RNG k−ε viscous model with enhanced wall treatment was applied to solve the flow problems.

Boundary conditions for the simulations were determined experimentally in the engine dynamometer test cell. Engine operation mode with power output 83.3 kW and crankshaft rotation speed 1600 rpm was chosen for the current simulation research. Key parameters used as boundary conditions in the simulation study are shown in Table 1. For all 3 models, the same conditions were used that allowed for the comparison of mixing characteristics and the study of the flow behaviour of the air and biogas mixture in the models.

Table 2. Boundary conditions

BC name	Type	Temperature, K	Mass flow rate, kg/s	Species
Air inlet	mass-flow inlet	300	0.1	
Biogas inlet (1 injector)	mass-flow inlet	300	0.0014	CH_4 and CO_2
Biogas inlet (4 injectors)	mass-flow inlet	300	4x0.00035	CH_4 and CO_2
Mixture out	outflow	–	–	–
Inlet Manifold	wall	–	–	–
Biogas injector	wall	–	–	–

In the current study 30% of the diesel fuel was substituted with biogas. The concept of "pre-purified" biogas was implemented with 60% methane and 40% CO_2 content.

5. Results and discussions

The analysis of the simulation results was done in the CFD post-processing module of the ANSYS software. The following parameters were analysed: 3D velocity and 3D CH_4 mass fraction (gradient) distribution in the inlet manifold, surface velocity distribution at the manifold outlets. Separately, obtained results related to 3D CH_4 mass fraction (gradient) distribution was analysed in terms of the homogeneity of the air-biogas mixture formed in the intake manifold. Here, CH_4 was chosen because it is the only combustible component of the mixture. Finally, the optimal location of the injector was offered.

Visualizations of CFD calculation results of flow velocity and CH_4 mass fraction (gradient) distribution in the inlet manifold for 3 different locations of fuel injector/injectors are shown in Fig. 11 to Fig. 13 and Fig. 17 to Fig. 19.

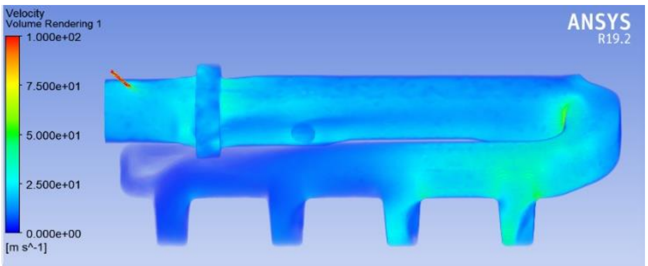

Fig. 11. 3D velocity distribution in the intake manifold (model 1)

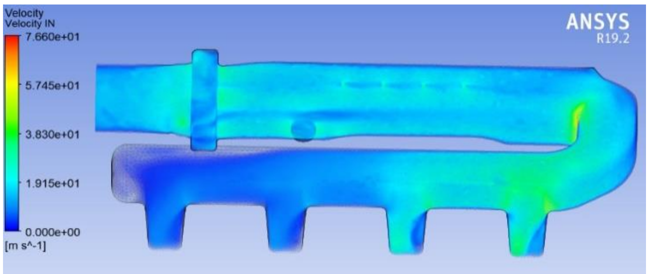

Fig. 12. 3D velocity distribution in the intake manifold (model 2)

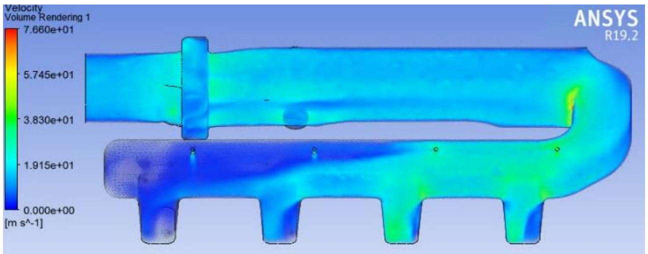

Fig. 13. 3D velocity distribution in the intake manifold (model 3)

As can be seen from Fig. 11 to Fig. 13, regardless of injector locations, there is an uneven velocity distribution in the regions corresponding to manifold outlets. Higher flow velocities were observed at the outlets 4.3 and lower at 2.1. To complement 3D velocity research, a surface velocity distribution at the manifold outlets analysis was conducted. Results are shown in Fig. 14 to Fig. 16.

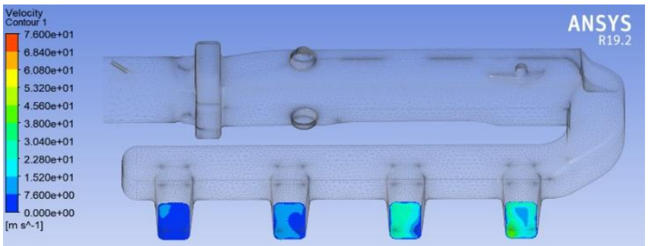

Fig. 14. Velocity contours at the outlets from the manifold (model 1)

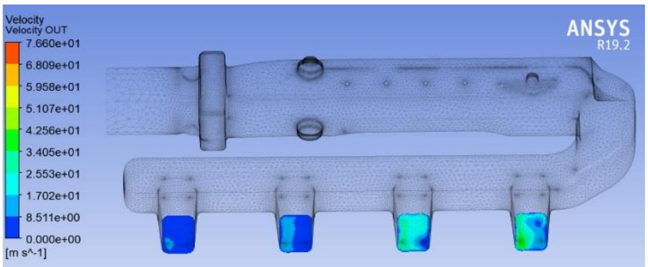

Fig. 15. Velocity contours at the outlets from the manifold (model 2)

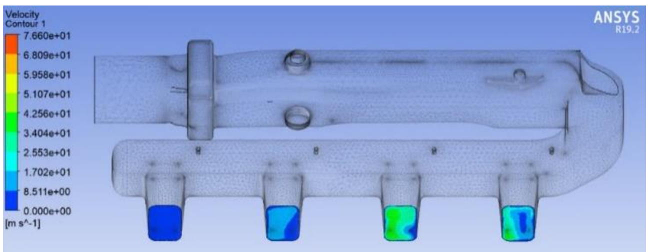

Fig. 16. Velocity contours at the outlets from the manifold (model 3)

It can be concluded from Fig. 14 to Fig. 16 that the highest velocity fluctuations could be established for the outlets 4 and 3, which will result in a higher flow turbulence rate for these outlets. Additionally, the air-biogas mixture average velocities at the manifold's outlet were defined. Results are shown in Table 3.

Table 3. Mixture average velocities at the outlet from the manifold, m/s

Model	Mixture Out 1	Mixture Out 2	Mixture Out 3	Mixture Out 4
Model 1	13.8	13.62	15.24	20.17
Model 2	13.91	13.85	17.23	20.21
Model 3	15.22	14.27	16.92	19.45

It could be concluded that in order to make the velocity distribution at the outlets more uniform, it is recommended to redesign the inlet manifold and make it more straight than curved.

At the final stage of the simulation analysis, a 3D mass fraction (gradient) distribution for CH_4 was studied. Results are shown in Fig. 17 to Fig. 19. Here, for the studied models, a characteristic zone where homogeneity of the air-biogas mixture is formed (or weakly formed) could be established.

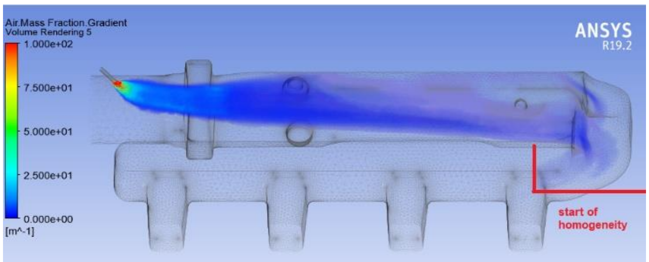

Fig. 17. CH_4 mass fraction (gradient) distribution in the inlet manifold – model 1

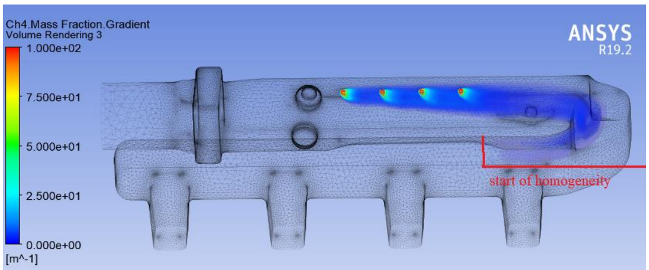

Fig. 18. CH_4 mass fraction (gradient) distribution in the inlet manifold – model 2

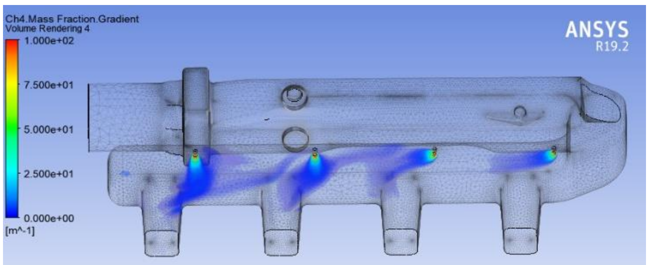

Fig. 19. CH_4 mass fraction (gradient) distribution in the inlet manifold – model 3

As it can be seen from Fig. 17–19, there is a risk of air-biogas non-homogeneity at the inlet to the engine cylinders for the model 3 (Fig. 19). At the same time model 1 and model 2 characterized by the minimum risk for inhomogeneous air-biogas mixture delivering inside the engine's cylinders, but model 2 gives more uniform cloud structure of biogas in stratified mixture. Thus, the optimal location of the injectors is related to the model 2.

6. Conclusions

1. Sources analysis showed that there are disproportionately few papers devoted to the phenomena of biogas injection location , which is a decisive factor for the formation of the fuel-air mixture and has a significant impact on the operating parameters of the ICE. Therefore, in this paper the influence of the location of biogas injectors in the compression ignition ICE intake system on the selected characteristics of the air-biogas mixture introduced into the cylinders was investigated.
2. The reverse engineering technique was applied to reproduce the geometry of the commercial intake manifold. The 3D model obtained was used for further CFD analysis.
3. Simulations were conducted for 3 models; in the first model, there was only 1 biogas inlet (1 injector concept) located at the entrance to the manifold; the second and third models had 4 biogas inlets (4-injector concept) gathered in series and located at various distances from the manifold's outlet.
4. The main results of the CFD analysis are as follows:

– regardless of injector/injectors locations, there is uneven velocity distribution in the regions corresponding to commercial manifold outlets; higher flow velocities were observed at the outlets 4,3, and lower in 2,1; to make the velocity distribution more uniform, it is recommended to redesign the inlet manifold and make it more straight.

– there is a risk of air-biogas non-homogeneity at the inlet to the engine cylinders observed in model 3, where 4 injectors were located close to the manifold's outlets; model 1 (with one injector) and model 2 (4 injectors) were characterized by the minimum risk of inhomogeneity for air-biogas mixture delivered inside the engine's cylinder, at the same time model 2 gives more uniform cloud of biogas located in stratified mixture, that's why biogas injectors location from model 2 is considered as optimal in this study.

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Nomenclature

CFD	computational fluid dynamics
CNG	compressed natural gas
ICEs	internal combustion engines
PM	particulate matter
RNG	renewable natural gas

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