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INFLUENCE OF GAS INJECTOR POSITION ON THE PERFORMANCE OF A DUAL-FUEL DIESEL ENGINE

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ABSTRACT – Combustion of gaseous fuels in dual-fuel engines requires appropriate way of fuel delivery and preparation of the combustible mixture. The gas injector is typically mounted in the intake channel close to the intake valve. The tests described here were conducted to answer the questions concerning: 1) the impact of the gas injector location in the tangential or helical channel on the creation of the charge; 2) the thermodynamic parameters of the operation of the engine supplied with gaseous fuel through different intake channels; 3) the assessment of toxic components in exhaust gas emissions for two variants of injector locations.
In the research it was stated that the supply of gaseous fuel through helical channel increases the intensity of fuel mixing with air resulting in the improvement of some thermodynamic parameters (e.g. IMEP) and in increase of nitrogen oxides concentration.

INTRODUCTION

Combustion of gaseous fuels in dual-fuel engines requires adequate preparation of both fuels for combustion, and the presence of the other fuel in the combustion space changes boundary conditions of this process. Explanation of certain selected aspects of this issue was the main inspiration for the research discussed herein.
In the case presented in this article, liquid fuel (diesel) was the ignition dose and was injected into the cylinder under high pressure, enabling its good atomization and a quick evaporation. Gaseous fuel (in this case – CNG) was the main energetic component of the process, however, creation of mixtures and preparation for combustion were conducted in worse conditions. The fuel was delivered to the intake channel at relatively low pressure and required suitable additional processing in order to achieve flammability and proper distribution in the combustion chamber. One of the aims of this publication was the assessment whether better engine operating indexes will be achieved by delivering gaseous fuel through the helical or tangential intake channel.

1. ANALYSIS OF LITERATURE

Assessment of the mixture creation quality during fuel injection into the intake manifolds in different shapes is carried out mainly with the use of simulation studies (1, 6). Benny and Ganesan (1) presented three models of intake manifolds meshes: spiral, helical and helical-spiral manifold. As a result of simulation studies it was found that the highest value of so-called swirl ratio is obtained using the helical-spiral channel (value of approx. 4 in the vicinity of TDC at n = 3000 rpm). In this case the swirl ratio was higher by about 25% compared to the study with helical channel. But the highest values of turbulent kinetic energy (TKE) of the charge were achieved using the helical channel. This means lower losses of energy dissipation in such a channel. This tendency was confirmed by the highest values of volumetric efficiency stated for this type of channels.
The optical tests concerning charge swirl in the cylinder were conducted by Czajka et al. (2). During the tests optical methods were used for determining the swirl ratio of a charge in

the cylinder of a combustion engine. The change of the swirl ratio was obtained through variable opening of the intake channels: helical and tangential. As a result of the research it was possible to determine the swirl ratio of the charge, based on the analysis of the combustion process shots. Subsequent publications of the authors (3) enabled determination of the value of the charge swirl during the various phases of flame formation. For significant swirl the degree of swirl, on the basis of the video observation, amounted to approx. 5, and for the low swirl the value amounted to 1–1.5.

The optical analysis of flame swirl was conducted by Wislocki et al. (11) in a rapid compression machine. Using different configurations of air injector location in the combustion chamber, the conditions change of the charge swirl was obtained. In the machine the swirl ratios ranging from 1 (air and gas supplied perpendicularly to the cylinder axis) to 3 (air and gas supplied coaxially, tangential to the cylinder axis) were obtained.

The experimental studies with the use of an optical swirl sensor were also carried out by Vanhaelst et al. (10). For the analysis of the results the PIV and HSV (High Speed Video) methods were used. The obtained results confirmed the applicability of the optical sensor for the determination of the peripheral swirl in the cylinder of a compression-ignition engine during its operation. For several combustion chambers the swirl conditions were determined at the engine speed of n = 1200 rpm. Also the increase rate of the swirl ratio of a charge during the upward movement of the piston was determined, and the maximum value of the swirl ratio of 6 was found at TDC. The use of the optical sensor made it possible to determine a correlation between the results obtained from the calculation with the use of 0D models, and the swirl defined by the optical sensor.

Previous studies the authors of this paper (7, 8) indicate that the increased interval between doses of fuel for single-fuel supply results in an increased cumulative heat release. This leads to the conclusion that it is necessary to intensify the processes in the combustion chamber in order to reduce the preparation time of combustion charge.

Research carried out by Kooka et al. (4) indicates that the swirl ratio of the charge of about 3-4 during the injection of diesel obtains high combustion efficiency with low emissions of carbon monoxide. Perini et al. (5) in a study on the flow through the tangential and helical channels, implemented throttle valves in each channel. As a result of this change, it was possible to adjust the swirl ratio of the charge in the cylinders of the engine. In the above mentioned test, along with the experimental studies also model tests were carried out.

Dual-fuel supply of the engines increases the potential for development of such engines as, which was demonstrated by Reitz (9), obtaining a lean charge with value of $\lambda > 1$ contributes to filling-in a so-called low emission window. Reitz indicates that this window relates to the value of the air excess ratio $\lambda = 1.1–3.0$ and a maximum temperature of combustion of approximately 1800 K.

A significant potential of supplying an engine with natural gas is observed for injection systems localized in the vicinity of the intake valve. In this way the volumetric efficiency increases, as the injected gas does not displace the air from intake channel.

The research presented in this paper focused on the possibility of determining the changes of thermodynamic parameters of the combustion process when supplying the engine with gas from one of two channels: tangential or helical. Selection of a particular option has impact on variable mixing of fuel and air in the combustion chamber. In dual-fuel engine an ignition of a charge prepared in different ways is initiated with a dose of diesel fuel. Due to the optimal mixing of gaseous fuel with air it is possible to obtain a smaller value of the initial dose (causing ignition) of diesel fuel.

2. METHODOLOGY

The study described in this paper was carried out on a four-valve single-cylinder test engine with the displacement of 510.7 cm^3 manufactured by AVL. The most important technical data have been collected in the Table 1.

Table 1: Technical data of the research engine AVL 5804.

Parameter	The value and unit
Engine displacement	510.7 cm^3
Piston course	90 mm
Cylinder bore	85 mm
Compression ratio	16.2
No. of valves	4
Injector type	piezoelectric, 8-holes, d = 0.117 mm
Type of injection system	Common-rail

The engine was equipped with the direct injection of diesel fuel. The gaseous fuel (compressed methane) is being supplied to one of intake channels by Bosch electromagnetic injectors, located very close to the cylinder head: either to the helical channel or to tangential channel.
The engine was coupled with the test-brake of the asynchronous AMKASYN-170-4-AOW generator of DW13 type with the possibility of adjusting the brake for constant engine speed.
The test stand (Fig. 1) was equipped with control and measuring apparatus including:
a) system for fast-varying processes measurement AVL IndiCom 621 enabling measurement of pressure in cylinder with the use of pressure sensor AVL GH14D with the measuring range of 0–250 bar and sensitivity of 18.84 pC/bar,
b) a system for data acquisition AVL Concerto,
c) a system for control of the diesel injection process enabling the control of the injection time and injection angle with resolution of $\Delta\alpha$ = 0.5 deg CA and fuel pressure up to 200 MPa by Mechatronika Poland,
d) a dual system for process control of gaseous fuel injection with resolution of 0.1 ms within the range up to 20 ms at fuel supply pressure up to 10 bar by Mechatronika Poland,
e) the system of measuring gaseous components – Horiba Mexa 7100D for type approval testing measuring CO, THC (HFID), NO_x and CO_2.

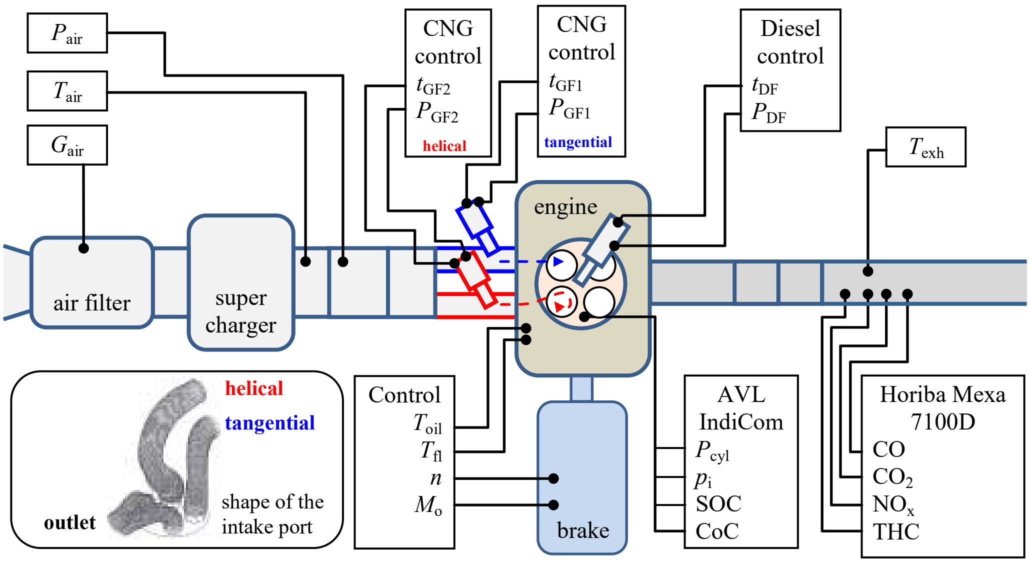

Figure 1: Diagram of the engine test-bed configuration and measuring points of the listed operational indexes.

The tests were carried out for different engine loads using interchangeably gas injection into the straight (tangential) or helical channel. During the measurements the following parameters were determined:
a) engine operational indicators,
b) thermodynamic indexes of the charging and combustion processes,
c) emission of exhaust gases (determined on the based on measurements of CO, HC and NO_x concentration with the use of values of engine operation indexes).
The following measuring procedure was adopted: in every measurement point the fast-varying processes (100 cycles repetitions) were recorded with the use of IndiSmart system

by AVL. The analysis of exhaust gas emissions was carried out with the use of Horiba Mexa 7100D system enabling dynamic recording of gaseous components concentration in the exhaust gases.
The tests were carried out at the engine speed 2000 rpm and for constant ignition dose of diesel of q_o = 6.33 mg/inj ($t_{inj\text{-}DF}$ = 0.25 ms was kept const; it corresponds to 3 deg CA at 2000 rpm). Change of the load was obtained by increasing the time of the injection of natural gas dose ($t_{inj\text{-}GF}$) from 0 to 8 ms (corresponds up to 96 deg CA at 2000 rpm). These conditions were applied during separate injection into each of the two intake channels. The gas injectors were located tangent to the axis of the two intake channels so that the gas was injected into the stream of air and not onto the collector wall. Conditions during the tests are presented in Table 2.

Table 2: Conditions of the tests.

n [rpm]	$t_{inj\text{-}DF}$ [ms] @ 700 bar	$t_{inj\text{-}GF}$ [ms] @ 9 bar	overall lambda limit [–]
2000	0.25	0; 2; 3; 4; 5; 6; 7; 8	5.4; 3.6; 2.7; 2.1; 1.8; 1.5; 1.3; 1.15

As the ignition dose of diesel was constant, it represents from 100% (in the absence of gas injection), to approximately 23% (at a higher engine load) of energy supplied with fuel. During the analysis it was found that doses of liquid fuel can be burned using any method of supplying gaseous fuel (using any intake channel). The increase in the share of gaseous fuel with growing engine load results in significant changes in the thermodynamic parameters of the process.

3. INFLUENCE OF GAS INJECTOR POSITION ON THE CONDITIONS OF DUAL-FUEL DIESEL ENGINE

3.1. The conditions in the cylinder during fuel injection and compression

The gas injection consequences with the use of tangential or helical channel are already visible during the phase of mixing the natural gas with air during delivery of the charge into the combustion chamber. The beginning of the methane injection occurred always at the angle of –320 deg of crank angle (CA) (when 0 deg CA denotes TDC), that is for the open intake valve. The valve opened at the angle of –370 deg of crank angle before TDC, allowing the injection of the entire dose (the maximum dose of gas was injected by 96 deg of CA) during opening of the intake valve. Closing of the intake valve took place at an angle of –134 deg of CA before TDC. For this point of closing the intake valve, the cylinder charge temperature was calculated based on the thermodynamic analysis of the indicating diagram (Fig. 2a). Next, the self-ignition temperature of the charge was estimated for various engine loads (Fig. 2b).
As it can be observed from the Fig. 2a, the injection of gas into the helical channel results in lower charge temperature which indicates better mixing with air when compared to the injection into the tangential channel. The differences in temperatures amount to approx. 10 degrees, despite of engine load. This regularity is also confirmed by the calculations of temperature the start of diesel fuel injection (Fig. 2b). In this case, the temperature of the charge delivered through helical channel also has a lower value. However, with the increase in the share of gas (lower lambda value) this difference decreases from more than 10 degrees to about 5 degrees.

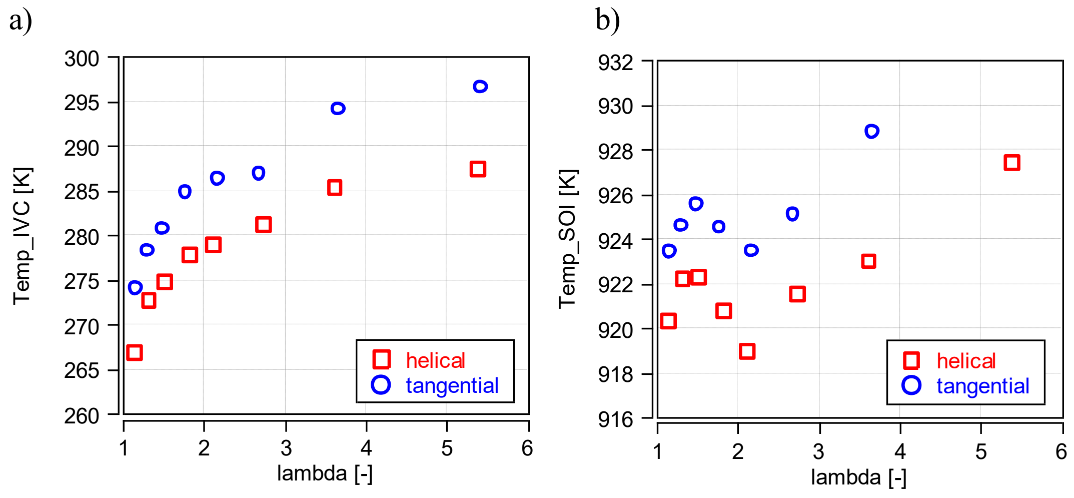

Figure 2: The characteristics of the changes of intake valve closing temperature (a) and the self-ignition temperature of fuel (b) for engine fueled with ON and CNG gas, depending on the value of the air excess ratio – lambda.

The consequence of the lower temperature values in the combustion chamber during gas injection through the helical channel is also lower average temperature during self-ignition (SOC) – Fig. 3a. This lower value of temperature along with the earlier angle of the combustion start (Fig. 3b), indicates a better preparation of the charge for combustion compared to the injection of gas into the tangential channel. The self-ignition conditions do not differ much; however, there is a constant trend that indicates the earlier self-ignition of fuel for gas injection into a helical channel which was shown in the analysis of all measuring points.

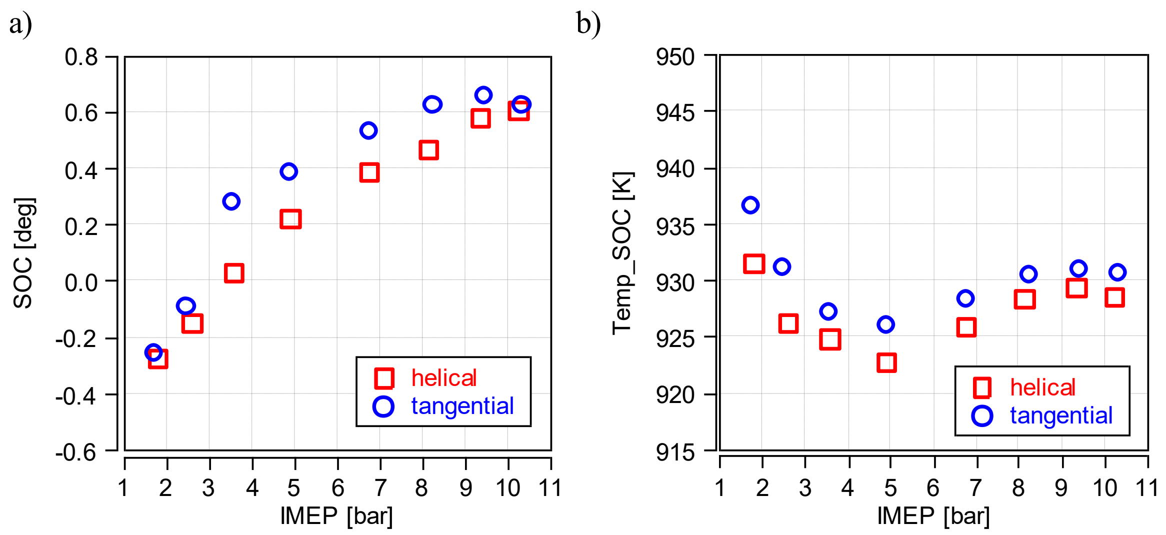

Figure 3: The impact of the average engine load (for 100 cycles) on the average value of the start of combustion angle (a) and the cylinder charge temperature at the SOC (b) for fuelling engine with CNG through two different intake channels.

3.2. The thermodynamic conditions in the cylinder during combustion

Comparison of the characteristics of pressure changes in the cylinder (Fig. 4) for supplying gas through different intake channels indicates an earlier start of the combustion process for the gas injected into a helical channel. However, with the increasing load, the difference in pressure in the cylinder in both cases decreases. Slightly higher pressure values are obtained at the maximum dose of gas supplied into a tangential channel, which indirectly indicates a better combustion process in this case. What it means is, that large doses of gaseous fuel do not require intense swirling in the combustion chamber, and that the positive impact of the use of the injection into the helical channel is noticeable for low and medium engine loads.

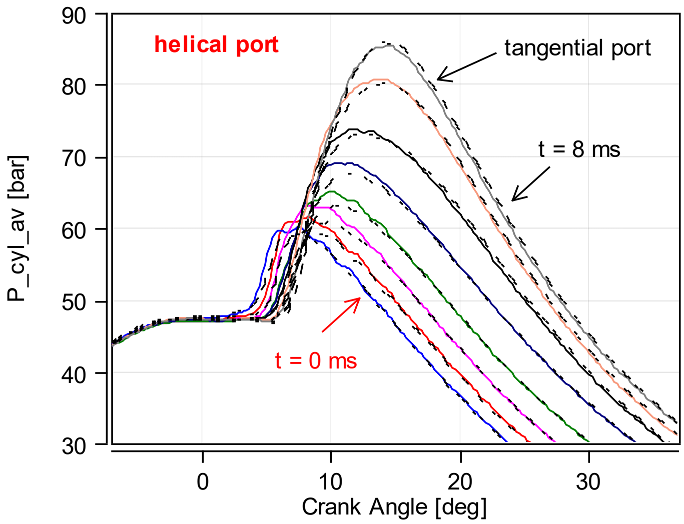

Figure 4: The characteristics of the cylinder pressure during fuelling engine with ON and CNG (solid lines – injection through helical channel, break line – through tangential channel).

The presented conditions of charge preparation should result in different combustion processes of the gas injected into the engine through tangential or helical channel. Analysis of the maximum pressure of combustion in the cylinder indicates that within the range of medium engine loads these changes are the most significant. Supplying gas through helical channel increases the homogeneity of the charge, resulting in an increase in Pmax in the cylinder (Fig. 5). Analysis of the non-uniformity of operation of the engine supplied through different channels, however, does not indicate the existence of any significant differences. In both cases, CoV(Pmax) does not exceed 5%.

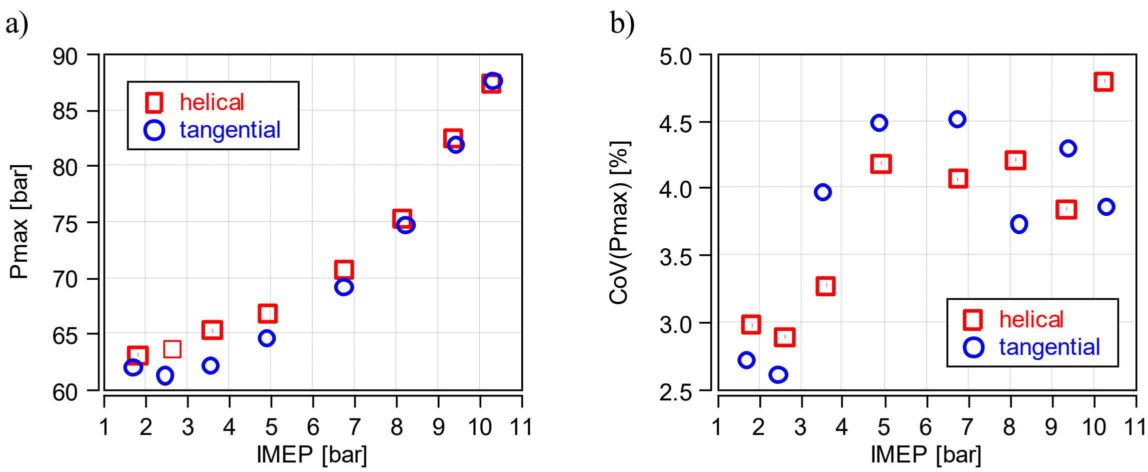

Figure 5: Changes of the maximum combustion pressure at different values of load for averaged cycles (a) along with the dispersion of this value (b) during supplying the engine with CNG through each of the intake channels.

The analysis of the process mean temperature does not indicate significant differences when changing the way in supplying the engine (Fig. 6). However, the value of this temperature increases for high loads of the engine supplied through tangential channel (gas injection time above 4 ms). Despite better preparation of the charge during injection through helical channel within the range of lower loads, during the injection of high doses this positive effect is not observed. The process can be negatively influenced by low value of air excess ratio under a heavy load.

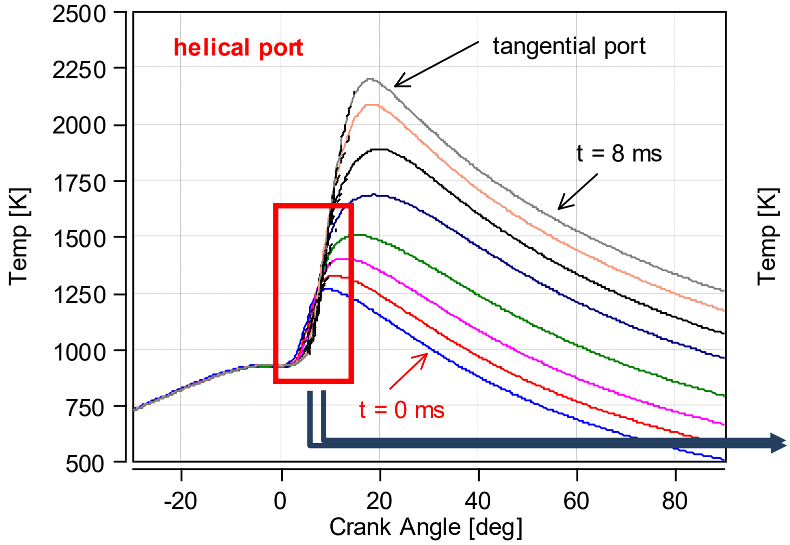

Figure 6: The characteristics of the mean temperatures of the charge in the cylinder during fuelling engine with ON and CNG (solid lines – injection through helical channel, break line – through tangential channel).

Analysis of heat release indicates an earlier start of the combustion process (MBF5%) for the gas injected into a helical channel (Fig. 7) compared to an engine supplied through tangential channel. In the dual-fuel engine was observed a quick first phase of the process (small difference of MBF50%–MBF5% angles). Also the elongation of the afterburning phase was observed.

Combustion of mixtures in conditions of partial loads features the longest times (or largest angles) of process duration. Lower load values cause a slight increase in the duration of the second phase of the combustion. With increase of the load, the share of this phase exceeds 60% of the total combustion process duration. Fuelling engine through the helical channel does not cause any significant reduction of this process.

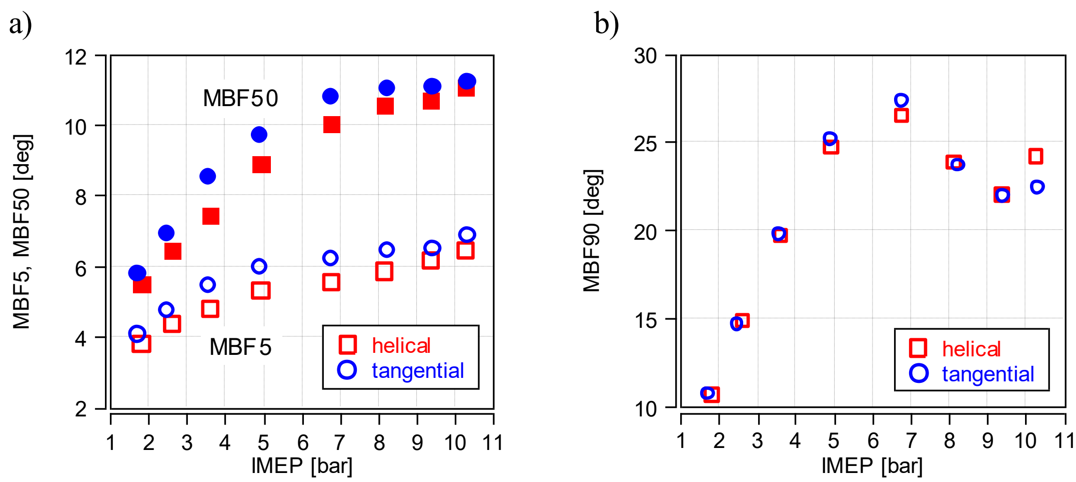

Figure 7: Influence of the engine load on 5%, 50% (a) and 90-percent value of mass burned fuel (MBF) (b) for engine fuelled with CNG through each of the intake channels.

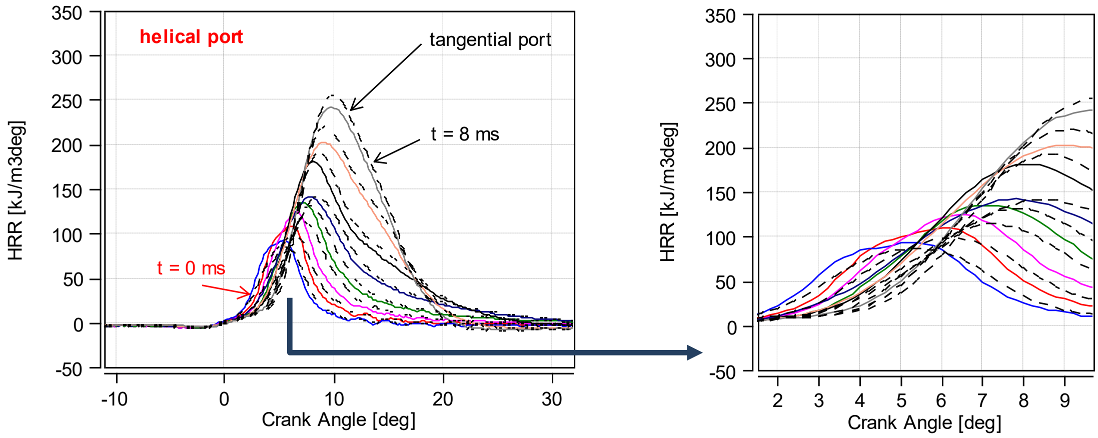

Figure 8: The heat release rate in the cylinder during fuelling engine with ON and CNG (solid lines – injection through helical channel, break line – through tangential channel).

3.3. Emission indexes of the combustion process

The parameter verifying the quality of combustion process is the toxic emission components in the exhaust gases. For engine supplied through the helical channel the combustion process started earlier and better mixing of fuel with air was obtained. The positive effects are also observed in the analysis of the exhaust emission. The analysis of these parameters (Fig. 9) indicates the existence of a positive correlation between the way of supplying the engine and the nitrogen oxides emissions. An increase in the intensity of the pre-flame process results in higher values of nitrogen oxides emissions. These changes are not significant, but this trend mainly concerns low and partial loads. The carbon monoxide and hydrocarbons emission does not allow for an indication the clear trends, suggesting no significant impact of different ways of supplying engine with gas on the emission of these substances.

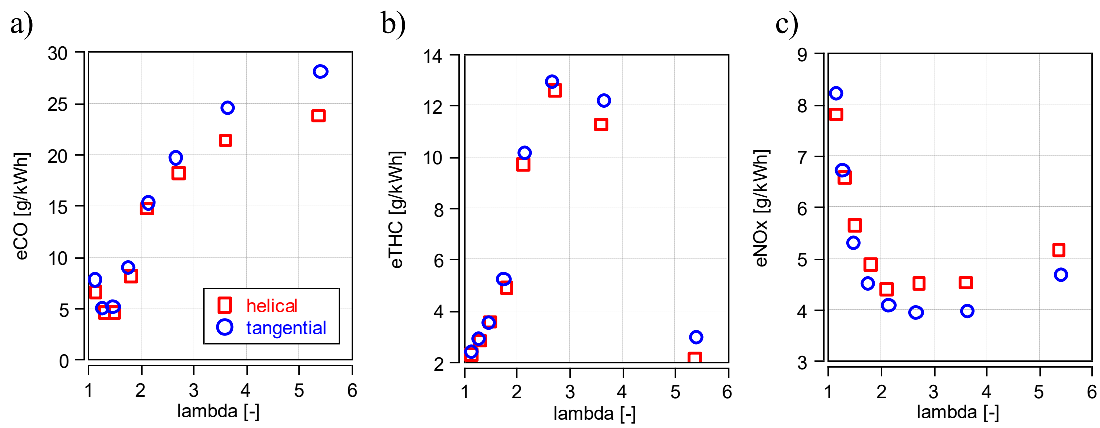

Figure 9: The influence of air excess ratio on the specific exhaust emission of: a) CO, b) HC and c) NO_x for engine supplied with ON and CNG through each of the intake channels.

4. CONCLUSIONS

Summarizing the results of the research and analysis carried out, authors concluded that:

a) gas injection into a helical channel brings certain advantages during the pre-flame process, as well as during combustion of small and medium doses of fuel,
b) supplying large gaseous fuel doses into the cylinder does not require strong swirl of the charge and the beneficial effect of the use of helical channel fades,
c) the values of the exhaust gases emission during heavy engine loads do not depend on way how the gas injector is placed in the helical or tangential channel; within small loads a beneficial effect of injection into the helical channel was observed, and better mixing of the charge contributes to the increased emissions of NO_x and lower value of CO.

The shape of the intake channel has just a minor effect on the generation of the charge

movement inside the combustion chamber located in the piston crown, while the shape of the intake channel significantly affects the movement and structure of the charge outside the combustion chamber and during the phase of pre-flame processes.
Also the following additional detailed conclusions were formulated:

1. The injection of gas to the helical channel results in better mixing with air and in lower charge temperature in comparison to the injection into the tangential channel. The differences in temperatures amount to approx. 10 degrees, despite the engine load.
2. Lower temperature value at the start of combustion and earlier angle of the combustion start for injection into the helical channel indicate a better preparation of the charge for combustion compared to the injection of gas into the tangential channel.
3. Higher values of the maximum combustion pressure were obtained for injection of gas into the helical channel. With the increasing load, these difference decrease. This means that injection of large doses of the gaseous fuel does not require intense swirling in the intake manifold.

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NOMENCLATURE

CoV – coefficient of variation (of Pmax)
e – exhaust emission
HRR – heat release rate
IMEP – indicated mean effective pressure
MBF – mass burned fuel
Pmax – maximum cylinder pressure
P_cyl_av – average cylinder pressure (of 100 cycles)
SOC – start of combustion
TDC – top dead centre
Temp_SOC – cylinder charge temperature at start of combustion
Temp_IVC – cylinder charge temperature at angle of intake valve closed
n – engine speed
t_{inj-DF} – injection duration of diesel fuel
t_{inj-GF} – injection duration of gas fuel

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