

Computational study of influence of inflow port channel design on spark-ignition natural gas engine parameters

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Abstract. Resistance is The article presents the results of the research of a charge swirl motion influence on working process, engine parameters and NOx emissions of a spark ignition premixed natural gas engine. The charge swirl motion was organized by tangential inflow channel. The engine work process research was performed using numerical modeling of physical and chemical processes in combustion chamber. The turbulent flow in combustion chamber, spark ignition and combustion of gas fuel were simulated. The simulation shows that a tangential channel allowed organizing a swirl motion of charge and increasing turbulent kinetic energy of flow in the combustion chamber. Swirl motion greatly affects the combustion process. The increase in the turbulent kinetic energy to the spark timing made it possible to substantially reduce the combustion time of the fuel. Replacement of one original channel by a tangential channel allowed reducing emissions of nitrogen oxides NO_x. Physical and chemical processes in combustion chamber were simulated in Ansys Forte.

Key words: natural gas engine, spark ignition, inflow channels, tangential channels, swirl motion, combustion modelling, emissions of nitrogen oxides, diesel to natural gas conversion

1 Introduction

Many natural gas spark ignition engines are now used. Natural gas fuel has several advantages over other motor fuels. Good antiknock properties, favorable mixture formation conditions, wide ignition range in mixtures with air and other positive properties of natural gas fuel provide high technical and economic performance of engines. Also gas engines have lower exhaust emissions, which make them more environmentally friendly.

Most natural gas engines are using converted relatively large, diesel engines. There are several studies about diesel to natural gas conversion [0, 2]. There are two ways to solve this problem. The first way involves the use of rich mixture, with slow combustion and minimum amount of in-cylinder flow velocity and turbulence. These factors should reduce the maximum pressure and temperature during the cycle and nitrogen oxides (NO_x) should

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then be low. Also these factors should reduce the heat loss to the walls and hence improve efficiency.

The second way involves the use of lean mixture, with fast combustion, maximum amount of in-cylinder flow velocity and turbulence, higher compression ratio. The level of NO_x should be very low with this strategy as the lean mixture would give a low maximum temperature. In this paper, the second path with the lean mixture is considered.

The thermal efficiency and exhaust emissions of natural gas fueled spark ignition engines highly depend on in-cylinder flow, mixture formation and combustion. To understand these characteristics is very important for improving the engine performance. These papers [3-9] are about processes that occur in a gas engine combustion chamber.

In present paper, a working process with a lean mixture is considered. It was shown in [10-12] that the turbulence of the charge in the combustion chamber increases the turbulent burning rate of the mixture. In order to accelerate the combustion of the mixture, it is necessary to intensify the motion of the charge in the combustion chamber. It was shown in [0, 2] that the effect of the combustion chamber shape on the intensification of charge motion in the engine cylinder was considered in detail. The present article is about how the inflow channels shape influence on a charge swirl motion, a flow turbulization in an engine cylinder, a combustion rate of the mixture, an environmental performance and on an engine indicator values.

The object of this paper is to investigate how the combustion tangential inlet port design will influence on combustion parameters and emissions in a natural gas spark ignition engine. One way to organize a charge swirl motion in combustion is to use tangential inflow channels [13]. Angles α and β are the main parameters for the tangential inflow channels profiling (fig. 1).

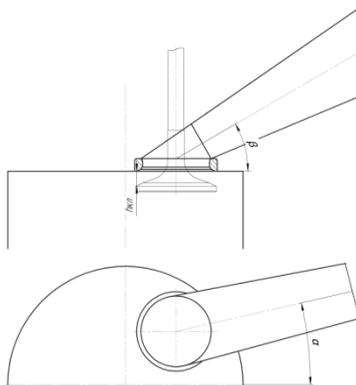


Fig. 1. The tangential inflow channel scheme.

2 Methods

There are a complex of physical processes in the combustion chamber, for example, turbulent flow, spark ignition and turbulent combustion of natural gas. In the study, these processes were numerical simulated by using a program Ansys Forte [11]. The most popular models for modeling turbulent flows are the Reynolds-Averaged-Navier-Stokes (RANS) models [15, 16]. $k-\epsilon$ turbulent model is of the most common models among models of this class. In this paper was used its modification – RNG $k-\epsilon$ turbulent model.

Nowadays, there are many different approaches to modeling of a combustion. The G -equation model was used to modelling of natural gas combustion in the combustion chamber. Discrete Particle Ignition Kernel (DPIK) model was used for modelling of a spark ignition [14, 17].

Knock may be considered to take a place when the energy released due to the preignition reaction activity within the end gas becomes sufficiently significant and intense that results in autoignition of a portion of the mixture yet to be consumed by the propagating flame. The knock criterion K_d [18-20] used in the present model is based on the assumption that the calculated accumulated amount of energy release due solely to end gas preignition reactions activity per unit of the instantaneous cylinder volume, relative to the total energy released normally through flame propagation over the whole cycle per unit of cylinder swept volume exceeds for knock certain acceptable levels.

$$Knock\ Criterion\ K_d = \frac{\frac{Preignition\ Energy\ Released\ by\ End\ Gas}{Cylinder\ Volume} \Big|_t}{\frac{Total\ Energy\ Released\ By\ Combustion}{Cylinder\ Volume} \Big|_{t_0}} \geq K_{cr} \quad (1)$$

Equation (1) may be simplified as:

$$K_d = \frac{(h_{st} - h_t)m_u/V_t}{h_0m_0/V_0} \quad (2)$$

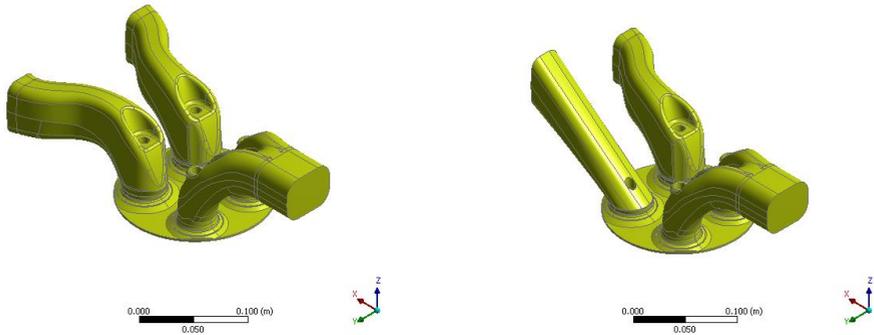
where h is the specific enthalpy of the mixture and μ is the instantaneous end-gas mass determined from the two zone model. V is the cylinder volume. Subscripts t_{st} and t indicate the values at the instant of spark discharge and at any time, respectively. h_0 is the effective specific heating value of the charge and m_0 is its initial mass.

This work is a continuation of previous research of Diesel to Natural Gas Conversion [21-23]. Table 1 shows the characteristics of the engine type CHN 15/17.5.

Table 1. Engine characteristics.

Parameter	Parameter value
Engine type	four-stroke
Number of cylinders in the engine	12
Piston stroke, m	0.175
Cylinder diameter, m	0.150
Geometric compression ratio	11
Connecting rod length, m	0.318
Crank shaft speed, rpm	1900
Equivalence ratio	1.4
Inlet pressure, bar	2.2
Outlet pressure, bar	2.1
Inlet temperature, K	345
Fuel	natural gas
engine fuel supply	carburation

Figure 1 shows the computational domain with original inflow channels and with tangential inflow channel. In present study hemispherical combustion chamber was used.



Original inflow channels
Fig. 1. Computational domain.

With tangential inflow channel

3 Results and Discussion

The engine work process research was performed using numerical modeling of physical and chemical processes in combustion chamber. Filling process, compression process, turbulent flow in combustion chamber, spark ignition and turbulent combustion of gas fuel were simulated.

For each variant of the geometry of the inflow channels, simulations were made for different values spark timing. Figure 3 shows that with a decrease in the value spark timing, the knock criterion increases. For each variant of the geometry, the value of spark timing corresponding to the value $K_{dmax}=1.5$. K_{dmax} is the maximum value of knock criteria over the engine cycle. This value of the knock criterion was recommended by the authors of the article [20]. The value of spark timing $\theta = -11.4^\circ$ is for original channels, for geometry with a tangential channel is $\theta = -9.7^\circ$. Further in this study, parameters of the two variants of the engine geometry corresponding to these spark timing values are compared.

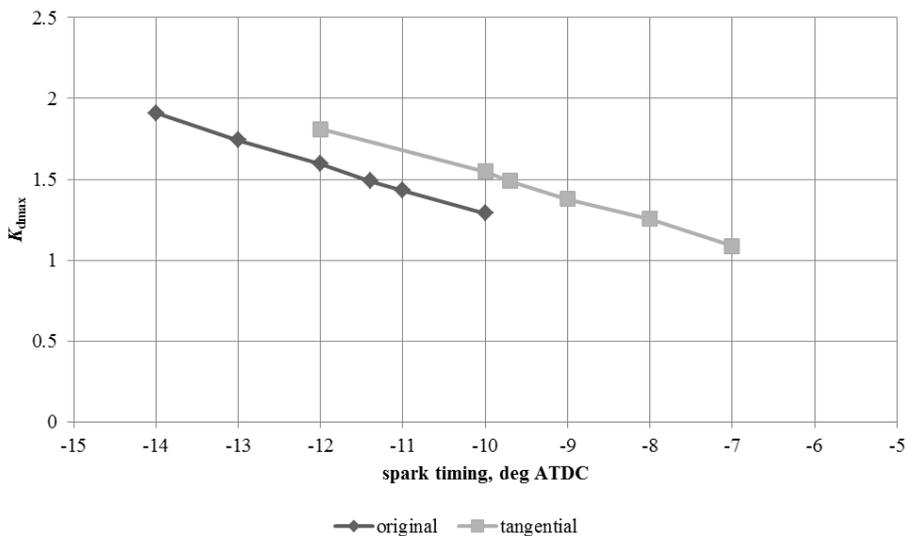


Fig. 2. The values of the knock criterion depending on the spark timing value.

The tangential channel is used to create a swirl motion in the engine cylinder and increase turbulence of the charge before the combustion process begins. At the spark timing in the geometry version with a tangential channel the swirl ratio=2.69. And in the version with original channels swirl ratio=0.01. At the spark timing in the geometry version with a tangential channel the averaged turbulent kinetic energy in the combustion chamber $k=110 \text{ m}^2/\text{s}^2$. And in the version with original channels $k=90 \text{ m}^2/\text{s}^2$. These values show that the tangential channel allows successfully creating a swirl motion and increase turbulence of the flow in the combustion chamber. With the entrainment of turbulent kinetic energy, the combustion rate of the fuel increases. Therefore turbulization of the charge has allowed reducing the time of combustion of fuel in the version with the tangential channel. The value of 10%-90% Heat Release Duration for the version with tangential channel is 14° , for version with original channels is 18° .

Figure 2 shows the shape of the flame front for different values of crank angles. To visualize the flame front, an isosurface corresponding to the value $G = 0$ is constructed. In this case, for two versions of channel geometry the spark timing value $\theta = -10^\circ$ was taken. It can be seen that the flame front spreads faster in the combustion chamber with a tangential channel.

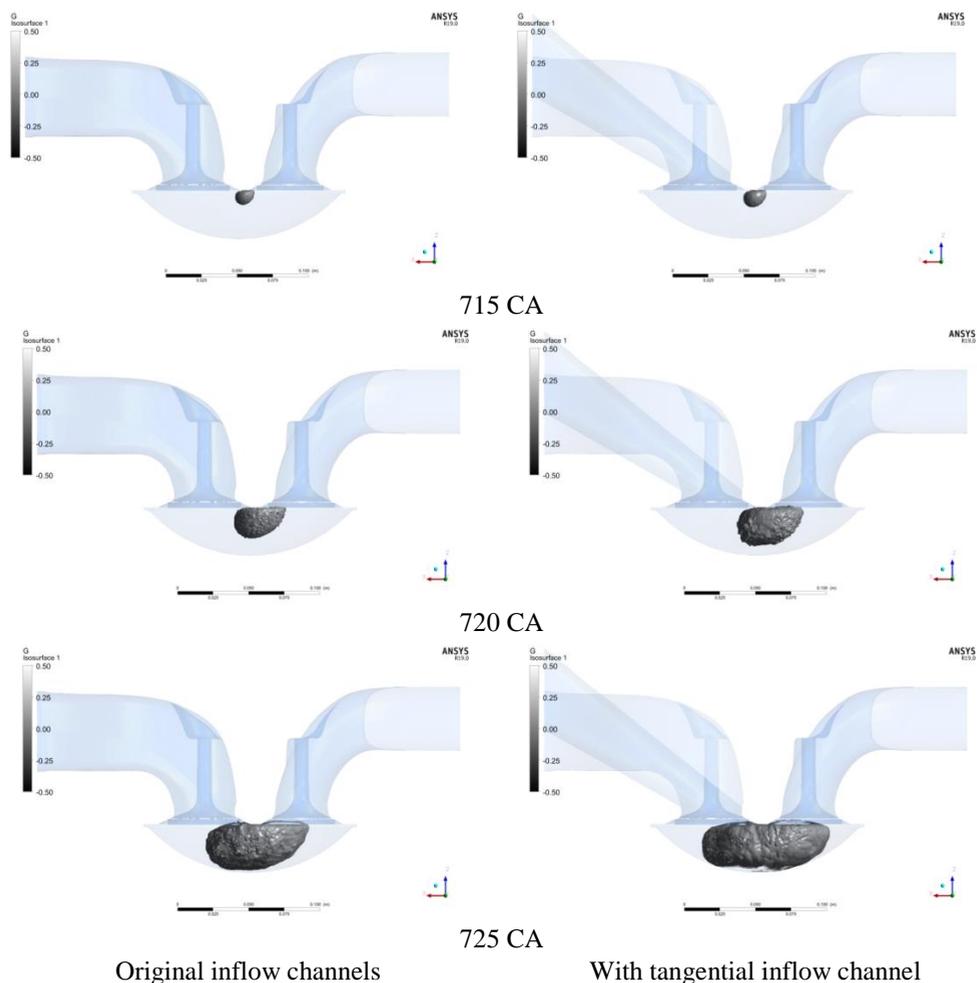


Fig. 3. The front of the flame for different crank angle values.

Table 2. Engine performance.

	Original inflow ports	With tangential inflow port
Spark timing θ , °	-11.4	-9.7
Knock Criterion K_{dmax}	1.49	1.49
P_{max} , bar	112	119
T_{max} , K	2245	2325
Swirl Ratio	0.01	2.69
Averaged Turbulent Kinetic Energy k , m^2/s^2	90	110
Mean Indicated Pressure P_i , bar	18.8	18.7
Gross Indicated Power N_i , kW	92.0	91.5
Thermal Efficiency η_i , %	52.10	52.12
Total Wall Heat Transfer Loss, kJ	0.94	1.23
Cooling Loss Ratio, %	7.4	9.7
10%-90% Heat Release Duration, °	18.0	14.1
NO _x emissions, g/kW·h	18.5	18.2

Table 2 shows the performance of two versions of geometry. An increase in the combustion rate leads to an increase in the maximum values of pressure and temperature of operating cycle. For the version with tangential channel $P_{max} = 119$ bar, $T_{max} = 2325$ K. For the version with original channels $P_{max} = 112$ bar, $T_{max} = 2245$ K. The organization of swirl motion in the combustion chamber increases the heat exchange of the flow with the wall. The total heat flux to the walls increases by 30%, from 0.94 kJ to 1.23 kJ. The combustion rate of the fuel has increased, but at the same time, heat losses to the walls of the combustion chamber have also increased. This led to the fact that the values of the P_i , N_i , η_i practically are close in value for the two versions of the geometry of the inflow channels.

In the version with tangential inflow channel emissions of nitrogen oxides NO_x decreased by 2%.

4 Conclusions

Numerical modeling of the working process in a gas engine with spark ignition was carried out for two variants geometry of inflow channels. Based on the results of work, the following conclusions can be drawn.

Replacement of one original channel by a tangential channel allowed organizing a swirl motion of charge and increasing turbulent kinetic energy of flow in the combustion chamber.

Swirl motion greatly affects the combustion process. The increase in the turbulent kinetic energy to the spark timing made it possible to substantially reduce the combustion time of the fuel.

The spark timing was chosen based on the value of the knock criterion $K_{dmax}=1.5$. For the original channels, the angle $\theta = -11.4^\circ$, for geometry with a tangential channel – $\theta = -9.7^\circ$.

The tangential channel increases the heat loss to the walls of the combustion chamber. Therefore the indicator values for the two versions of the geometry are close in value.

Replacement of one original channel by a tangential channel allowed reducing emissions of nitrogen oxides NO_x by 2%.

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