Pneumatic injection system using a hot exhaust gases, developed in Institute of Automobiles and Internal Combustion Engines of Cracow University of Technology

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Abstract. The article concerns research carried out by the Krakow University of Technology on the concept of a pneumatic fuel injection spark ignition engines. In this article, an example of an application of this type of power to the Wankel’s engine, together with a description of its design and operating principles and the benefits of its use. The work was carried out over many years by Prof. Stanislaw Jarnuszkiewicz despite the development of many patents but not widely used in engines. Authors who were involved in the team-work of the team of Prof. Jarnuszkiewicz, after conducting exploratory studies, believed that this solution has development potential and this will be presented in future articles.

1. Introduction

40 Years “Konmot” conference gives an excellent opportunity to summarize these achievements especially that the authors of this article are derived directly from the scientific Institute of Automobiles and Internal Combustion Engines, with is the main organizer of the conference. For this particular reason, the authors proposed to publish a series of articles on the development of the unique concept of a pneumatic fuel injection for spark ignition engines, which concept was design was designed and developed by prof. Stanislaw Jarnuszkiewicz and his team. The Authors of the publication were for many years part of this team, and this way they try to commemorate a Professor and carry on to remember his achievements and carry on with his ideas.

In the introduction leading to the habilitation monograph, which was created during the first and second “KONMOT” conference. Professor indicate in his publication that ... There were already performed some tests at this time to use direct fuel injection on an industrial scale, in order to eliminate... large defects of two-stroke engines ... [1]. The two-stroke engines in spite of faults, due to the simplicity of design, the two stroke engines were always the point of interest for Professor. Simultaneously he was gifted designer with great intuition and the ability to deploy scientific problem into practice.

These attempts until today have not passed the test on a larger scale, because of the coast of an injection systems which were also complicated and required professional services. These particular reasons mention above undermined obviously their attractiveness.
In the course of this work, Professor made a number of patents relating to the use on a pneumatic direct injection system, in internal combustion engines - the first in 1956. Nevertheless, however the concept of pneumatic fuel injection using the exhaust gases proposed by Professor, still has growth potential, according to the authors’ opinion. In the next series of publications, will be presented the results of studies indicating areas of possible applications of this system.

2. Hybrid engines
The dynamic development of pneumatic injection system according to the concept of Professor, occurred in the years immediately following the first oil crisis in the early seventies. There was established the cooperation with companies such as Volvo-Penta and Audi-NSU. Due to the marketing requirements, the pneumatic injection system has been called, the pumpless fuel injection system. Due to the unique characteristics of this injection system which ensured to engines with spark ignition, according to the classification of P. Schweitzer [2], identified them as hybrid engines. On the basis of this classification so called hybrid engines, an engines which combine the characteristics of spark ignition and compression-ignition engines, and their objective is to combine the advantages of both groups of engines. With the help of the injection system the stratification of charge relatively easily was obtained and qualitative power control, and the possibility of the use of liquid fuels with different fractional composition and exhaust gas recirculation. At present, after years of work in this field, each of these features can be subjected to sophisticated regulation by means of mechatronic equipment. However, there was no such possibility forty years ago, but that did not deter Professor to examine eleven prototype of engines.

As a result of stage control tests, carried out at the Cracow University of Technology in cooperation with the companies mentioned above, there were obtained in comparison with produced at that time Swedish and German low power engines, reduce fuel consumption up to 40%, with the use of gasoline and diesel. Achieved a reduction up to 90% of the content of toxic components of exhaust gas, carbon monoxide and hydrocarbons. Moreover they reached, a non-knocking combustion of liquid fuels with low octane number at constant compression ratio, and a wide range of qualitative power control. Examples of the characteristics will be presented later in this article.

3. Example of application with selected research results
The principle system developed by professor describe the use of the exhaust gases from the first cylinder with a relatively high pressure to spray the dose of fuel and inject it to the other cylinder and reveres.

Based on this principal simultaneously Professor has developed and patented injection system for two-stroke two-cylinder, three-cylinder, four-cylinder and six-cylinder engines [3]. Has also developed an adaptation of the four-stroke two-, four- and six-cylinder engines, as well as for rotary piston engine (Wankel) [4] [5]. Undoubtedly the most interesting example of application, was modified Wankel engine. Figure 1 shows the functional diagram of the solution, taken from the patent description.

As we know, over the years, the engine of this type was in the next stage of development, however, has not gained the expected level of the quantitative application. Especially recognition of accuracy of the diagnosis deserves more and proposed and documented test results, quoted in the article, the technical solution to the problem of oversize environmental burden of this type of engine. As an example, one can cite the following description [1]. Wankel type engines with rotary piston have in comparison with reciprocating engines, some differences of combustion, in addition to about 1.7 times larger faces the combustion chamber at the same volume. Therefore, in the exhaust gas of these engines there are relatively large amounts of unburned hydrocarbons and carbon monoxide with an increased specific fuel consumption. Based on previous research performed on Wankel’s combustion engines, one can outline the directions to reduce the adverse effects occurring in them, for define efforts to the reduction of exhaust emissions, which include:
removing particles or vapors of fuel, from the layer of boundary sidewall and from the narrowed cylinder space,
- concentration of combustible mixtures, mainly in the ahead portion of the combustion space and filling, the keeping up part of combustion space, mostly clean air, i.e. creating a stratification of charge, allowing the engine to operate also in the field of a large excess of air.

This assumption can be achieved bringing the gaseous fuel (fuel vapor) to the combustion chamber, wherein the stream of blown gas of low puncture strength, doesn’t reach to the walls of the chamber, and concentrate in the central portion. The direction and phase of blow of fuel vapor should be selected so, that they focus on the overtaking part of the combustion space… end of citation.

The principle of operation of the device executing the above command is as follows (description according to Figure 1): in so-called cold bow side of engine body, done two channels 1 and 2. The ducts join together in the mixing cell 3, to which is applied the fuel in controlled quantities. The moment in which the front sealing strip 4 reveals the outlet channel 2, takes place the blow hot exhaust gas from the combustion chamber 6 through the passageway 1, the cell 3 and the orifice 2 to the charge of air in the space 5. The hot exhaust gases lead to pushing the dose of the fuel from cell 3, to atomize and evaporating, and then blows to the air charge. The fuel supply to the mixing cells occurs after exposure by the sealing strip, the channel 1, that is, during the duration of low pressure in the channels. This cycle is repeated synchronously with the cycles of the engine. The study was conducted on a prototype engine with rotary piston type Wankel - NSU KKM-613/VI.

Basic technical data:
- one rotary piston,
- chamber volume: 498 cm$^3$
- compression ratio: 8.6: 1
- power output: 40 kW/6000 1/min
- maximum torque: 71 Nm/2500 1/min
- gasoline supply: Solex 18/32 HHD

Changing the way the engine power has required the development of a special dispenser. Functional diagram of the unit and installation in the Wankel engine, is shown in Fig. 2.
The Fuel dispenser comprises a housing 1, wherein the channels 2 are formed, supplying fuel, and fuel outlet channels 4 and also inlet gas channels 3 and outlet gas channels 5, for outlet gas which makes the injection of fuel. In the body 1 the rotational shaft 6 is set, having an accommodating space 8, the volume of which varies according to the position of the strip 7, actuated by the slider 16. During the rotation of the shaft 6, the space 8 is contacted with inlet channels 2 and outlet channels 4, for fuel discharging. This space has been filled with fuel, and excess of fuel flows by channel 4. After returning to a position in which the space 8 is contacted with inlet channels and through channels 5 for discharging the gas, is followed by gas extrusion one dose of fuel interposition contained in the space 8, to the injection system. The value of the dose depends on the volume of the space 8.

The operating indicators of the modified engine in relation to the carburettor supply, are provided in Figure 3.

![Diagram](image)

**Figure 2.** Functional diagram of the injection unit and installation in the Wankel engine.

**Figure 3.** The operating indicators of the modified engine in relation to the carburettor supply.
Visible limited range of crankshaft speed, due to the excessive length of the injection duct. This was due to the possibility of adapting the system of injection to the accessible location, limited possibilities of assembly.

It has been found that in applied injection pipe length, the engine less than 3000 l/min obtained, and in this field has a lower specific fuel consumption while maintaining comparable power.

Because on the test engine was not possible to shorten the gas duct, Professor has developed and patented the modified fuel injection system without pump, for engines of this type. Diagram of the device shown in Figure 4.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{modified_fuel_injection_system}
\caption{Modified fuel injection system for Wankel engines [1].}
\end{figure}

Unlike the previous system, the working space 5 and 7 of the engine is connected, to only one channel 2, which is located at the periphery of a trochoidal track, at the same location as the injection orifice previous version of system. This channel by this other part, is connected to the reservoir tank 3. Into this reservoir a certain amount of fuel is delivered (by channel 4), in the period, in which there is low pressure in the working chamber. During rotation of the rotating piston into the cartridge 3 flows a charge during the compression phase, then during the period of combustion and the start of expansion, flowing part of hot combustion gases under high pressure. Previously delivered dose of the fuel evaporated. At the moment, when the corner sealing strip of the piston 6 passes inlet channel 2, space of the cartridge 3 will be connected to the space 7 working chamber in which there is a low pressure (the end of the intake phase). The mixture of gases and vapors placed into the cartridge under high pressure, discharges by channel 2, into charge of air into the chamber 7. Implementation of this modification has brought next improvements in operating indicators of a modified Wankel engine. Obtained at that time results, are provided in Figure 5.

The specific fuel consumption was reduced by 15% and the content of carbon monoxide in the exhaust gas decreased repeatedly.
4. Summary
Positive results and relatively easy to realize application requirements, created by Professor Jarnuszkiewicz, supply and combustion systems, led him to a deeper study in the description of phenomena accompanying the process of fuel injection using hot exhaust gases. One of these directions was to study, the concept of binding insensitivity of modified engine at fuel tendency to knock, with the occurrence of chemical reactions such a cracking and pyrolysis, in the space of an injection cartridge. However, further research is conducted both by the professor and his colleagues have not confirmed this concept [6] [7]. Professor all its research activities tied to the Cracow University of Technology. In the last period of its activity at our University (until 2004) he conducted research on the issue of pneumatic injection to the multi-cylinder four-stroke engines. Despite the passage of years, his achievements of application in the form of granted patents, and completed construction of low power internal combustion engines, inspires admiration and respect, and is an excellent example for future generations of researchers and engineers.

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