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Research on improving the manufacture of injection nozzles in internal combustion engines

SUMMARY

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CONTENS

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INTRODUCTION

In the last decade, the development of manufacturing technologies has registered significant progress, especially in the field of vehicle construction, which has an increasingly large share in the production of pollutant emissions. Pollutant emissions produced by motor vehicles are mainly:

- carbon monoxide (CO);
- unburned hydrocarbons (HC);
- nitrogen oxides NO and NO2;
- particles (soot and ash).

Pollutant emissions produced by motor vehicles adversely affect air quality and are harmful to health. In order to meet the requirements of the environmental standards, various optimizations of the manufacturing processes and the use of materials with a low effect on pollution were resorted to. Although the current trend is to move to an electric vehicle propulsion, especially for transport in urban agglomerations, where the population density is very high and pollution is at very high levels thus endangering the health of the population, internal combustion engines still remain an element . very important for research, power development and high motor torques required for freight vehicles compared to electric motors.

In the last period, the optimization of fuel injection systems has made significant progress, which has the role of ensuring the atomization by spraying the fuel in the combustion chamber of the thermal engine. Its most significant development, the common rail technology that ensures high injection pressures (over 2700 bar), and which is used to optimize and create the fuel atomization process in the combustion chamber, resulting in the reduction of harmful combustion producers. fuel, providing flexibility and control during the operation of the thermal engine.

Air-fuel mixtures with high homogeneity produce shorter ignition delays, lower local temperatures and lower nox emissions due to increased energy delivery to the piston. Therefore, the quality of fuel atomization, evaporation and mixing significantly affects performance efficiency. Improving the performance of heat engines can be achieved by controlling the atomization and atomization of the fuel which depends on the fuel properties, the injector geometry and the flow conditions upstream and downstream of the flow ports (inside) of the injectors.

The main purpose of this research is to identify and study manufacturing technologies that can optimize the operation of injection systems used in motor vehicles to reduce pollution affecting the environment.

Thus, through the critical analysis of the researches and their results from the specialized technical literature (presented in PART I - The current stage of the researches and their analysis regarding the obtaining of the manufacturing processes of injection sprayers for internal combustion engines), of the theoretical researches carried out by modeling and simulating the flow of an abrasive fluid through the holes of an injection sprayer (presented in PART II - Theoretical studies and research on the manufacture of injection sprayer holes with abrasive flow assisted by ultrasound), as well as by conceiving, designing, making a hydroabrasive processing plants with ultrasonically assisted abrasive flow and the analysis of the experimental results obtained for the characteristics of the fluid flow through the fuel sprayer holes, respectively by using the processing plant made in the framework of these research studies, a rounding of the flow hole of the sprayer was obtained of fuel in the fluid flow inlet area

PART I – CURRENT STATE OF RESEARCH IN IMPROVING THE MANUFACTURING OF INJECTION INJECTION ENGINES

Chapter 1. Modern injection systems used in motor vehicles

Common rail injection systems compared to cam systems have the advantage that the pressure developed by the high-pressure pump is independent of the fuel injection made by the injector, allowing the pressure to be freely selected within certain limits. Thanks to the flexibility of this injection system, optimizing the formation and combustion of the fuel mixture in order to reduce pollution is easily achieved.

The first electronically controlled Common Rail system was launched by Bosch in 1997 for cars, which developed pressure of 1350 bar, followed in 1999 by a system for 1400 bar, and in 2004 the system that developed 1600 bar was launched on the market, currently reaching pressures of over 2500 bars.

A typical common rail injection equipment system with its main components is shown in figure 1.1. The pressure is developed independently of the injection cycle. The continuously running, engine-driven high-pressure pump delivers fuel that has been compressed to system pressure into the common rail, (6. Because of the near-uniform delivery, the size and maximum torque of the high-pressure pump is smaller than with systems of cam-controlled injection.

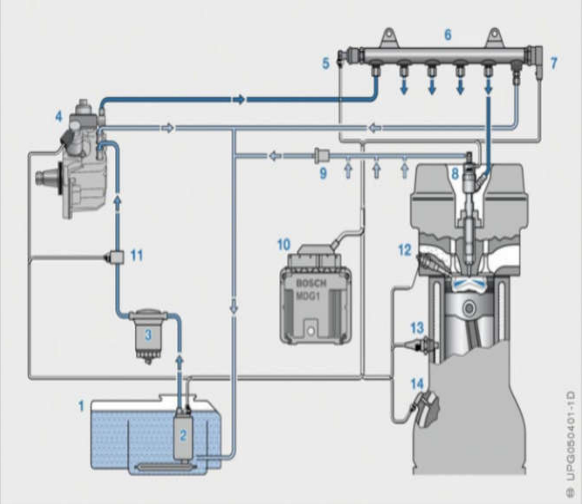


Figure 1.1. Common rail system for motor vehicles:

1 - tank; 2 - pre-charge pump with strainer filter; 3 - fuel filter; 4 - high pressure pump with measuring unit; 5 - pressure sensor on the ramp; 6 - common ramp; 7 - pressure control valve; 8 - injector; 9 - check valve (only for solenoid injector, optional) or pressure check valve (only for piezoelectric injector); 10 - control unit with inputs for sensors and outputs for servomotors; 11 - fuel temperature sensor; 12 - glow plug; 13 - cooling water temperature sensor; 14 - crankshaft speed sensor, [REI2020]

The opening time and system pressure determine the amount of fuel injected. It is therefore independent of motor or pump speed.

Common Rail systems have a number of advantages compared to cam injection systems, such as:

- the desired injection pressure is permanently available, regardless of speed and load;
- at low speeds and loads, high pressures can develop and thus the quality of the mixture improves;
- high flexibility regarding multiple injections, respectively their number and the distance between them;
- easy attachment to the motor and requires low drive torque.

In V-engines, each side of the cylinders is assigned a separate pressure ramp. The fuel supply from the pressure pump can be connected directly to one of the ramps or through a distributor block. The fuel accumulators (pressure ramps) are then connected to each other by a high-pressure line, with numerous connection and connection options.

In the high-pressure area of the common rail system, the generation and storage of pressure and also the measurement of the injected fuel are carried out, with the following components:

- high pressure pump;
- common ramp;
- pressure sensor;
- pressure regulation sensor;
- pressure limiting valve;
- high pressure pipelines;
- injectors.

The high pressure pump is driven by the engine. The gear ratio must be selected so that the fuel delivery rate is sufficient to achieve the nominal volume of the system. Additionally, delivery must occur synchronously with injection to achieve substantially the same pressure conditions at the time of injection. The fuel compressed by the high pressure pump is transported to the fuel rail through the high pressure line(s) and from there it is distributed to the connected injectors.

The common rail is used to store the fuel received from the high pressure pump and to supply the required amount of fuel to the injectors.

Common rail injectors are mainly composed of an injection sprayer, support body, control valve and control chamber, and ensure the atomization of fuel into the combustion chamber.

Chapter 2. Current State of Research and Analysis for the Improvement of Manufacturing Processes of Injection Atomizers for Internal Combustion Engines

From the analysis of research on the improvement of manufacturing processes of injection sprayers used in internal combustion engines, the following manufacturing technologies are noted:

a) Sequential laser microdrilling and EDM

b) Additive manufacturing of injection sprayers by Laser Powder Bed Fusion and Binder Jetting;

c) Advanced processing and finishing technologies with abrasive flux

From the analysis of the specialized literature studied, a series of research directions specific to injection sprayer manufacturing technologies emerged, for which there is not enough information, or no conclusive results were obtained..

The said analysis led to the following conclusions:

- Making fuel flow holes through injectors using sequential laser micro-drilling and EDM eliminates the disadvantages of EDM machining and laser use. The processing is done at low cost, but in return, the cost of the processing plant is high. An advantage of this method is the flow of machining fluxes during the drilling process, which reduces machining time and increases drilling efficiency.
- Additively designed and manufactured injection sprayers after testing indicated a high discharge and thermal regime. Through this manufacturing technology, a more homogeneous distribution of the fuel spray is obtained compared to the geometries obtained by classical technologies, thus determining the improvement of the combustion performances, but their durability is reduced due to the porosity that appears in the manufacturing process, a fact for which its use in the manufacture of complex components to be more restricted.
- The abrasive flux machining process is a complex process, as it depends on many factors.
- Materials with high hardness can only be machined by abrasion.
- The quality of the surface processed by abrasion depends on the properties of the abrasive material and the parameters of the processing regime, which have the highest weight.
- The abrasion process is characterized by: high precision, superior surface finish and high productivity.
- Some of the hybrid and derivative processes of the abrasive flux finishing process have some limitations depending on the machining principle and the particular arrangements of auxiliary dissociatives used.
- Relatively long finishing time and low material removal are the main limitations of the AFF process; therefore, research is still needed to optimize this processing process;

- No thorough research has been done on the abrasion machining of small-sized surfaces such as injection nozzles.

Chapter 3. Objectives of the doctoral thesis

From the analysis of the state of current research on innovative manufacturing technologies in the field of injection nozzles for internal combustion engines, the following research directions specific to this field emerged:

- improving hydroabrasive processing technology to increase performance and obtain an increase in the quality of small surfaces by optimizing process parameters;
- mathematical modeling of the hydroabrasive processing process;
- optimization of the parameters of the processing plant.

Taking into account the conclusions resulting from the analysis of the current state of research and the research directions, the following main objective of scientific research can be formulated:

"Conducting research on hydroabrasive processing with ultrasonically assisted abrasive flow, of the flow holes of injection sprayers used in internal combustion engines".

To fulfill the main objective, the following secondary objectives are necessary:

a) analysis and synthesis of current innovative research in the field of manufacturing injection sprayers;

b) studies and theoretical research for the improvement of manufacturing through numerical modeling and simulation of abrasive flow processing of injection sprayer orifices that assume:

- establishing the conditions for the modeling and simulation of abrasive flow processing of injection sprayer holes;
- creating the geometric model and meshing, (creating the mesh), the flow hole of the fuel injector sprayer;
- establishing the types of limits;
- carrying out the simulation;
- determination of the variation of the static pressure, the dynamic pressure, the turbulent energy, the turbulence intensity, the average flow velocity and the shear stress of the flow orifice wall, of the fuel atomizer, for the case of orifices with a straight inlet edge;
- determination of the variation of the static pressure, the dynamic pressure, the turbulent energy, the turbulence intensity, the average flow velocity and the shear stress of the flow orifice wall, of the fuel atomizer for the case of orifices with a rounded inlet edge;
- analysis and interpretation of the results obtained;

c) experimental research for the improvement of the manufacturing of the nozzles of the injection injectors used in internal combustion engines by processing with ultrasonically assisted abrasive flow, which involve:

- design and construction of the hydroabrasive processing plant with ultrasonically assisted abrasive flow:
  - establishing the necessary conditions for the realization of the hydroabrasive processing facility;

  - realization of the functional scheme of the hydroabrasive processing plant;
  - identification of the necessary components;
  - assembly of plant components;
  - carrying out functional tests and optimizing the operation of the installation;
- designing the experiment plan;
- carrying out the experimental study:
  - carrying out the hydroabrasive processing of the holes of the injection sprayers under the conditions established in the experiment plan;
  - testing and checking injection sprayers on the stand to check and test injectors:
    - the design and processing of the auxiliary components necessary to carry out the testing of hydroabrasive machined sprayers on the stand to check and test injectors;
    - determination of flow characteristics for hydroabrasive processed sprayers;
    - establishing the percentage ratio of the maximum flow of processed sprayers in relation to the maximum flow of the unprocessed sprayer;
  - analysis of the quality of the surface of the flow holes of the machined sprayers, (dimensional and roughness analysis);
- analysis and interpretation of experimental results.

PART II - THEORETICAL RESEARCH ON THE FABRICATION OF ULTRASOUND-ASSISTED ABRASIVE FLOW INJECTION SPRAYERS

Chapter 4. Ultrasonically Assisted Abrasive Flow Machining of Injection Sprayer Orifices

Considering the increase in the need to produce parts with complex surfaces and with a high degree of finishing at low costs and with a high level of pollution, the need for the emergence of processing processes that satisfy these requirements, namely abrasive flow processing, has also increased ultrasonically assisted, providing a finish with high accuracy and precision. This operation uses the abrasive particles to remove the material as a cutting tool [JJD1999]. An ultrasonic homogenizer is used to keep the abrasive particles in homogeneous suspension.

The abrasive flow machining system consists of the following components: hydraulic pump, hydraulic cylinders, pistons and auxiliary arrangements for fixing the workpiece (figure 4.1).

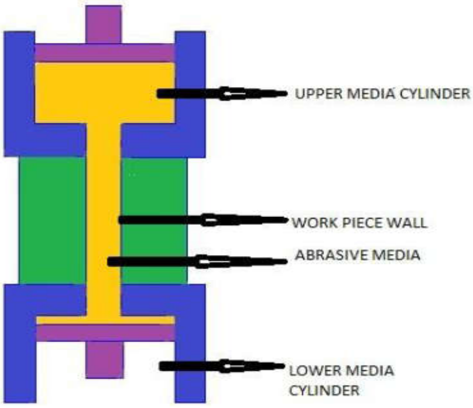


Figure 4.1. Abrasive Flow Machining Process, [WAS2014]

The hydraulic system forces the medium through the workpiece from one abrasive medium cylinder to another at a specific flow pressure (10 bar to 200 bar) of the abrasive fluid medium.

Since injection nozzles have holes that must have a good surface finish,

Fluid Dynamic Analysis, (CFD) has shown that abrasive particles hit the walls of the flow orifice of the sprayer at the entrance to the orifice, creating by impact with the orifice wall an internal erosion, [DAB2007], worsening the flow performance.

Research has shown that rounding the sharp edge of the injection nozzle orifice by hydroerosive machining reduces the effects of cavitation, [BWK1999].

From the analysis of the research on abrasive flux processing, we deduce that the main parameters that influence the results of the processing process are:

-extrusion pressure (the optimal pressure for improving the quality of the surface to be processed is 80 bars);

- the size and concentration of the abrasives (an improvement in the quality of the surface to be processed is obtained for concentrations of 10% and 20%);

- the amount (good results of finishing the surface on the machined are obtained for a reduced amount of fluid, respectively Vfluid = 1 l/pass) and viscosity of the abrasive fluid;

- the number of passes of the abrasive medium through the holes of the fuel sprayers (N= 4, 6, 8);

- working temperature (25 °C);

Abrasive flux machining is an advanced process that is commonly applied to finishing complex shaped parts to achieve better surface roughness and tighter tolerances.

Abrasive particles are very hard particles with irregular and sharp tips and edges, with the role of removing small chips from the surfaces to be processed. They have been known since the Neolithic, being used for polishing the surfaces of certain objects.

In order to be able to detach these chips, the abrasive particles must be entrained in a relative movement with respect to the surface of the part to be processed, being embedded in a solid material (discs and abrasive stones, etc.), fluid suspensions, in a jet of gaseous medium or in a magnetic field. The cutting tool in this case presents the abrasive particles which have randomly arranged cutting edges and which have different inclinations of the cutting tips.

The selection of abrasive particles used in abrasive flux machining is usually done according to three main criteria:

- according to the nature of the abrasive material;
- after granulation;
- the cost price.

These criteria for selecting abrasive materials are not independent, they are in close correlation with the material to be chipped, the type of processing procedure and the desired quality for processing. From the studies and analyzes carried out, it is found that the most used abrasive particles are those of SiC because they are cheaper and have a longer service life compared to other abrasives (Al_2O_3, B_4C, Garnet).

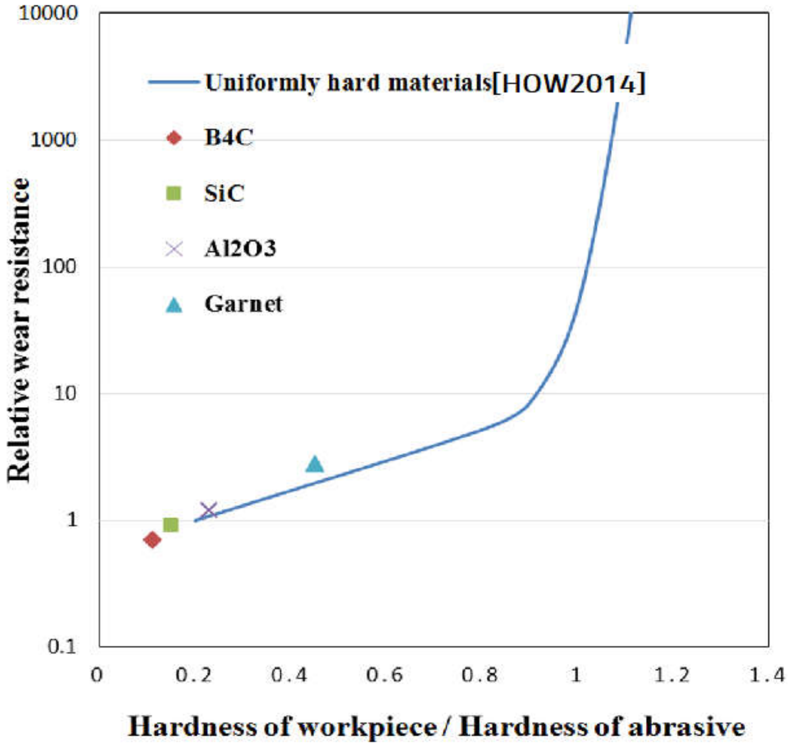


Figure 4.2. Variation of wear resistance as a function of hardness rate of tool steel X155CrVMo12-1 with a hardness of 55HRC, [KUO2016]

The improvement of the abraded surface is influenced by the wear resistance of the abrasive particles. The amount of material removed decreases with the hardness of the abrasive materials, respectively from B_4C→SiC→ Al_2O_3 →Garnet.

Taking into account the above, SiC abrasive microparticles will be used for this study.

Abrasive media are the main components of the hydroabrasive machining process, consisting of a viscoelastic polymer reinforced with abrasive particles, which act as a carrier medium, and the abrasive particles act as a cutting tool that ensures the removal of material from the workpiece. From the analysis of research specific to this field, it was found that the commonly used polymer media are polyborosiloxane and silicone rubber.

But in view of this fuel injector nozzle machining study, a fluid that has close characteristics to diesel fuel and ISO 4113 calibration fluid for diesel injection equipment will be used.

Table 4.1. Properties of diesel fuel and ISO 4113 oil

Properties	Diesel fuel	ISO 4113 oil
Density la15^{0}C [g/ml]	0,820	0,825
Kinematic viscosity [mm^2/s]	2,87	2,53
HFRR lubricity [micron]		410

This fluid has properties close to those of diesel fuel and is a mineral oil with a degreasing effect that protects the injectors after calibration allowing their operation after a period of storage at nominal parameters.

Chapter 5. Modeling and Numerical Simulation of Abrasive Flow Machining of Injection Nozzles

Since ANSYS Fluent provides comprehensive modeling capabilities for a wide range of compressible, incompressible, laminar and turbulent fluid flow problems, this software was used for the study. ANSYS Fluent combines a wide range of mathematical models for transport phenomena (such as heat transfer and chemical reactions) with the ability to model complex geometries.

The analysis of the flow of the fluid environment involves the following stages:

- creating the geometry model and meshing, (discretizing), the flow hole of the fuel injector sprayer;
- specifying the types of limits and implementing the problem in Fluent;
- the solution;
- analysis of the results.

For a rigorous analysis of the fluid flow through the sprayer orifice, two types of flow orifices are considered, respectively with a straight edge at the liquid inlet and with a rounded edge.

In this study, the characteristics of flow media through injection nozzles were investigated in terms of pressure profile, turbulence and wall shear in abrasive fluid flow process using ANSYS FLUENT software tool.

From the analysis of the distributions of the turbulence intensity of the fluid flowing through the injection sprayer hole, for the two cases respectively, with a straight edge and with a rounded edge, it is observed that in the case of the sprayer with a rounded edge, the cavitation phenomenon is significantly reduced, thus improving the flow characteristics and decreasing the undesirable effects of cavitation compared to the case of a straight edge sprayer.

From the analysis of kinetic energy distributions, it can be observed that turbulence dissipation and turbulent kinetic energy intensifies with increasing pressure, granulation and concentration of the abrasive, and presents a fluctuation due to the cavitation phenomenon in the entrance area of the flow hole. The higher the turbulent kinetic energy, the larger the area of turbulent flow. The more homogeneous the mixture, the better the consistency of the polish.

From the analysis of the shear stress distributions in the area of the edge of the nozzle hole for both the straight edge and the rounded edge, the following results are obtained:

– keeping the pressure and grain size constant, with an increase in the concentration of abrasive particles in the fluid medium, the shear stress in the edge area increases, thus reducing the finishing time in the hydroabrasive finishing of the edge, and if we reduce the concentration of abrasives, the finishing time increases;

– if the pressure and concentration of the abrasives, in suspension, remains constant, but we increasingly change the granulation of the abrasives, we notice that the shear stress is reduced, thus achieving an increase in the duration of finishing the inner surface of the sprayer hole;

– if the granulation and concentration of the abrasives are kept constant and we increase the extrusion pressure through the hole, an increase in the shear stress is obtained, thus causing a reduction in the edge finishing time.

From the analysis of the results of this study, the following major conclusions can be drawn:

- The fluid flow conservation equations were solved numerically on fully unstructured numerical grids, which allows the modeling of complex sprayer and cavitation phase geometries.
- The addition of ultrasonic vibration ensures a uniform maintenance of the abrasives in suspension thus achieving a uniform interaction with the surface of the workpiece, thus increasing the degree of material removal and improving the surface finish.
- Changing the geometry of the flow path of the workpiece, respectively changing the cross-sectional area, significantly influences the distributions of the pressure, velocity and wall shear profiles. By rounding the inlet edge of the flow orifice, cavitation is reduced, thereby increasing injection pressure, flow velocity and wall shear stresses, thereby improving flow characteristics.
- The extrusion pressure on the surface of the workpiece decreases along the length of the workpiece due to the interaction of the abrasive particles with the surface to be finished.
- The use of 80 bar pressure ensures the conditions for finishing the edge of the entrance wall by rounding in optimal conditions.
- Material removal rate increases with extrusion pressure and percentage concentration of abrasives in the medium, but its value decreases with abrasive grain mesh size.
- The wear rate is positively correlated with the flow rate at the same angular section of the fluid flow microchannel.

Numerical simulation results show that the improvement of material removal rate and surface quality depends on the abrasive particle size, respectively, the material removal rate is proportional to the abrasive particle size, while the surface quality is inversely proportional to it.

The results of this study were used to design the facility for the experimental research.

PART III. EXPERIMENTAL RESEARCH ON THE FABRICATION OF INJECTION NOZZLE ORIFICES BY ULTRASOUND ASSISTED ABRASIVE FLOW MACHINING

Chapter 6. The design and construction of the hydroabrasive processing installation with ultrasonically assisted abrasive flow

From the analysis of the current state of research, it is found that new experimental studies are needed regarding the improvement of the quality of the flow surfaces of the injection equipment, respectively of the injection nozzle holes that have a significant role in ensuring the quantity and quality of the fuel flow for combustion, with implications for combustion products influencing air quality. It is regulated by increasingly strict standards from this point of view. It should be noted that from the analyzed studies it is found that the method of maintaining the abrasive medium in suspension during processing is not presented, as well as detailed technical data of a processing facility of this level, a fact for which such a facility was designed.

When creating the hydroabrasive processing plant, the following requirements were taken into account:

- to achieve a high pressure of at least 80 bars (this condition results from the analysis of the current state and from the analysis of the simulation of the flow of the abrasive fluid through the holes of the fuel sprayer);
- to ensure the distribution of the erosive fluid at a well-determined moment;
- have a small size;
- to be economical in terms of manufacturing costs;
- to comply with occupational health and safety regulations and PSI.

The following components were used to create the installation:

a) electric motor;

b) pressure pump,

c) transmission through the trapezoidal belt;

d) high pressure pipelines;

e) pressure accumulator;

f) hydraulic pressure hoses;

g) hydraulic pressure regulation valve;

h) hydraulic ball valve ¾ with two ways;

i) check valve;

j) liquid pressure gauge for a maximum pressure of 160 bars;

k) double effect hydraulic cylinder;

l) telescopic damper for actuation of the double-effect cylinder;

m) fluid tanks;

n) the starting board;

o) ultrasonic vibration homogenizer;

p) mass of the installation;

r) injector port sprayer.

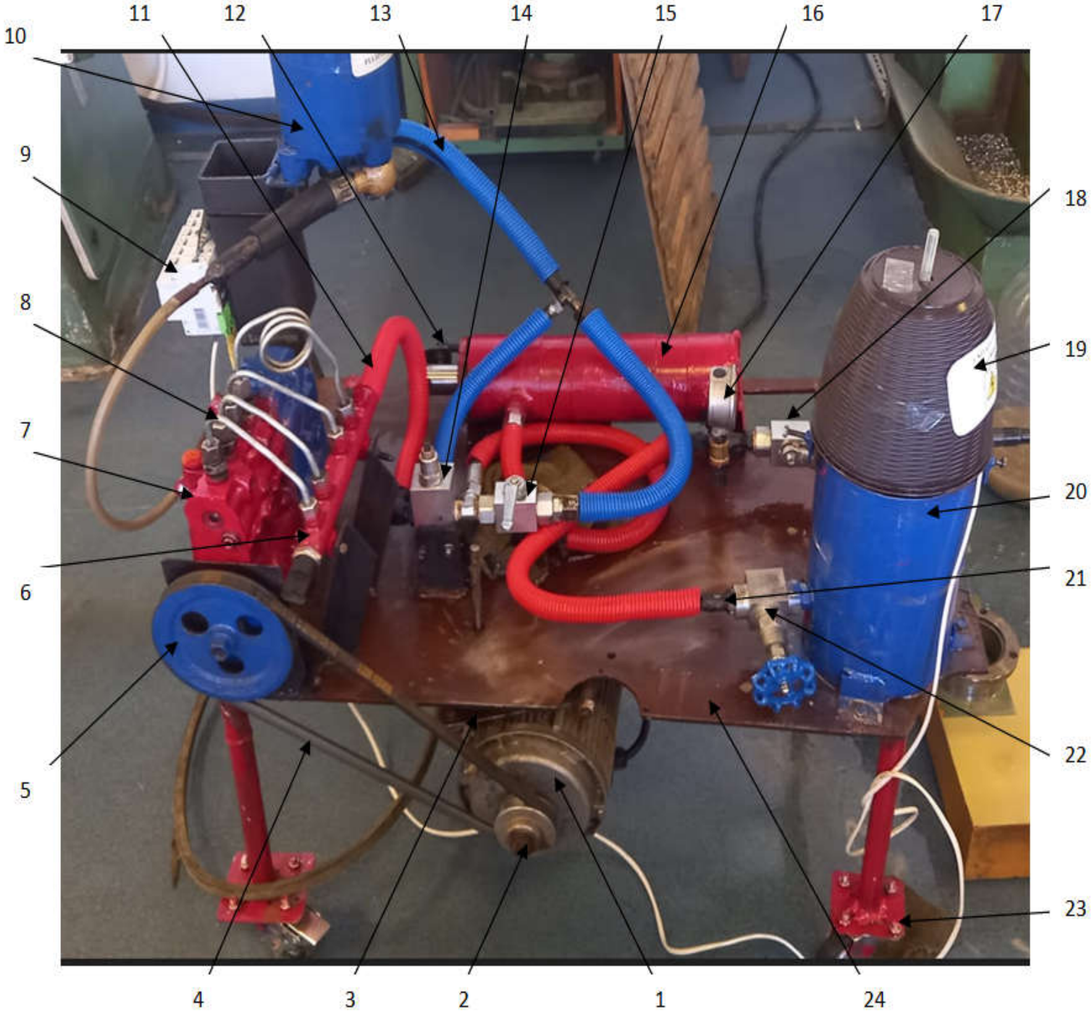


Figure 6.1. Hydroabrasive processing plant - general view: 1 - electric motor; 2 - driving belt wheel; 3 - engine stretching system; 4 - trapezoidal belt; 5 - driven belt wheel; 6 - pressure accumulator; 7 - injection pump; 8 - high pressure pipe; 9 - control panel; 10 - tank with hydraulic fluid; 11 - high pressure route; 12 - telescopic damper; 13 – low pressure route; 14 - pressure regulation valve; 15 - faucet; 16 - double effect cylinder; 17 - pressure gauge; 18 - faucet; 19 - ultrasonic homogenizer; 20 – tank with abrasive fluid; 21 - check valve; 22 - faucet; 23 - displacement rollers; 24 - table of the installation

Chapter 7. Experimental results obtained by hydroabrasive processing with ultrasonically assisted abrasive flow of injection sprayers

7.1. Designing the plan of experiments

From the analysis of the research carried out in the field of abrasive processing of injection sprayers, as well as from the analysis of the theoretical research from Part II of this research thesis, we deduce that in order to obtain optimal results, the experimental research will be carried out under the following conditions:

- the carrier fluid used is the calibration fluid - ISO 4113:2010 – Quantity: 2 liters;
- SiC abrasive powder, (silicon carbide), F800: 7 μm grain size, purchased from England through the company GERO TOOLS SRL from Sibiu-Romania;
- Concentration of abrasive particles in the carrier fluid: c = 0.1 dm3/liter and 0.2 dm3/liter;
- Extrusion pressure: 80 bars;
- Number of passes of the abrasive fluid through the fuel spray holes: 4, 6 and 8.

For the experimental study, type DLLA-150 P44 fuel sprayers will be used, which have intermediate treatment in the area of the flow channel (hardness is 51 HRC).

In order to carry out the experimental research, a complete experimental plan was designed, using the Minitab software product, having two factors, (Volume fraction, [%] and Volume of abrasive flux used for processing, [l]), each having two and three, respectively levels.

Table 7.1. The values of the parameters corresponding to the experimental research

StdOrder	RunOrder	PtType	Blocks	Volume fraction, [%]	Number of passes	Volume, [l]
4	1	1	1	20	4	4
6	2	1	1	20	8	8
1	3	1	1	10	4	4
3	4	1	1	10	8	8
2	5	1	1	10	6	6
5	6	1	1	20	6	6

The purpose of this design stage is to obtain experimental results with maximum accuracy.

7.2. Experimental results and discussion

In order to carry out the research on hydroabrasive processing of RO-DLLA-150 P44 type sprayers, reference 297.11.055, with 5 injection holes with ϕ=0.24 mm, with the installation angle of δ=150 °, 6 sprayers were used identical to the intermediate treatment applied to the flow holes of the injection sprayers. These intermediate heat treatments are practiced when the sprayers are intended to equip functional models or prototype engines, for which the injection equipment has a different configuration of the injection holes both in terms of diameter and angle of placement. This is a practice of all companies producing injection equipment for small series or for research.

For the experiments, the amount of carrier fluid and the amount of abrasive required for each individual test case were measured and weighed. The experiments were carried out with the six nozzles on the processing stand respecting the conditions established in the experiment plan and after each test the injector nozzles were marked (numbered) for identification

b)

a)

c)

Figure 7.1. The processing of injection sprayers: a) - functional presentation; b) - presentation of the spraying of the fuel jet in the collection tank; c) - presentation of SiC micropowder - F 800, and calibration oil 4113 used in processing

During the six experiments, the results presented in table 7.2 and table 7.3 were obtained.

Table 7.2. Variation in transit time of the abrasive fluid through the fuel spray ports

Sprayer	Amount of abrasive used [dm^3/ litru]	Passing time [s]								
		1	2	3	4	5	6	7	8	total
1	0,2	39,04	38,14	38,39	39,04					154,61
2	0,2	38,27	38,38	38,54	38,22	38,67	38,26			230,34
3	0,2	38,68	38,42	38,21	38,34	38,18	38,78	38,56	38,34	307,51
4	0,1	37,16	36,67	36,84	37,08					147,75
5	0,1	36,82	36,16	36,28	36,44	36,65	36,62			218,97
6	0,1	36,54	36,61	36,45	36,18	36,87	36,11	36,54	36,13	291,43

Table 7.3. Variation of average flow rate through the fuel injector ports

Sprayer	Amount of abrasive used [dm^3/ litru]	Average flow/passage velocity [m/s]								
		Pass number								Average/ sprayer
		1	2	3	4	5	6	7	8	
1	0,2	113,24	115,91	115,16	113,24					114,39
2	0,2	115,52	115,19	114,71	115,67	114,33	115,55			115,16
3	0,2	114,30	115,07	115,70	115,31	115,79	114,00	114,6	115,31	115,02
4	0,1	118,97	120,56	120,00	119,23					119,69
5	0,1	120,07	122,26	121,86	121,32	120,63	120,73			121,14
6	0,1	120,99	120,76	121,29	122,19	119,91	122,43	120,99	122,36	121,37

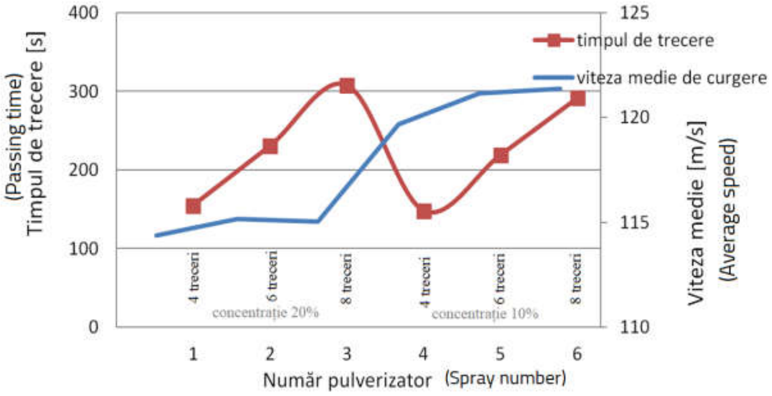


Figure 7.2. Graphs of the variation of average flow velocity and passage time through the nozzles of the fuel sprayers as a function of the concentration of the abrasive fluid and the number of passes

From figure 7.2 it can be seen that as the number of passes increases, the duration of the passage of the fluid through the orifice decreases and the flow rate increases, due to the phenomenon of wear of the abrasive particles during abrasion of the inner surface of the flow orifice of the sprayer.

Also, with the decrease in the concentration of the abrasive, an increase in the flow speed and a reduction in the duration of the period of passage of the abrasive fluid are observed.

Erosion efficiency is influenced by the pressure and velocity of the abrasive medium extruded through the workpiece.

After the machining of the injector nozzle holes, the injection characteristics were checked at the injector test bench, for different operating conditions.

Given that the sprayers used for processing cannot be mounted on piezoelectric injectors, we proceeded to make an adaptation nut for fastening on Delphi piezoelectric injectors COD A0C9F3E3 BE31F270, available at Service.

In order to be able to mount the sprayers on the metering plate of the Delphi injector, modifications were made to the original special nut that fixes the sprayer to the body, according to figure 7.3 you can see the configuration of the Delphi special nut.

For the adaptation intended for the installation of RO-DLLA-150 P44 sprayers, reference 297.11.055, on the Delphi injector body, a support bushing for the modified Delphi nut was designed.

By welding the two landmarks, the special nut for assembling the sprayer on the injector body was obtained.

In figure 7.3. shown is the adapter nut for mounting the sprayer to the injector body as well as a Delphi piezoelectric injector COD A0C9F3E3 BE31F270 that has the adapter nut installed.

a) b)

c)

Figure 7.3. Delphi injector: a) Delphi nut; b) manufactured nut; c) assembled Delphi injector

Also the sprayer needle is too long and the sprayer does not open in the Delphi injector, for which I proceeded to rectify it on the grinding machine to reduce the size from 4.5mm to 3.2mm, so by 1.3mm. The grinding machine used is shown in figure 7.4.

a) b)

Figure 7.4. UMG Cugir grinding machine: a) general presentation; b) the detail of the rectification process

Figure 7.5. Device for fixing the spray needle on the UMG Cugir grinding machine

In order to determine the flow rates for different injection pressures and different control times of the injector opening, we carried out tests, after which we obtained the injection characteristics for each sprayer, on a Hardridge Cri-PC model stand, type PED 97/23/ EC PS2000BAR (figure 7.6).

Figure 7.6. Hardridge Cri-PC injector test stand

Figures 7. 7÷ 7.12 show the injection characteristics for sprayers 1 6, raw. For all samples, the signal duration was: 400, 500, 600, 700, 800, 900 and 1000 μs, and the pressures in the feed ramp were: 35, 50, 70, 90, 100 and 120 MPa.

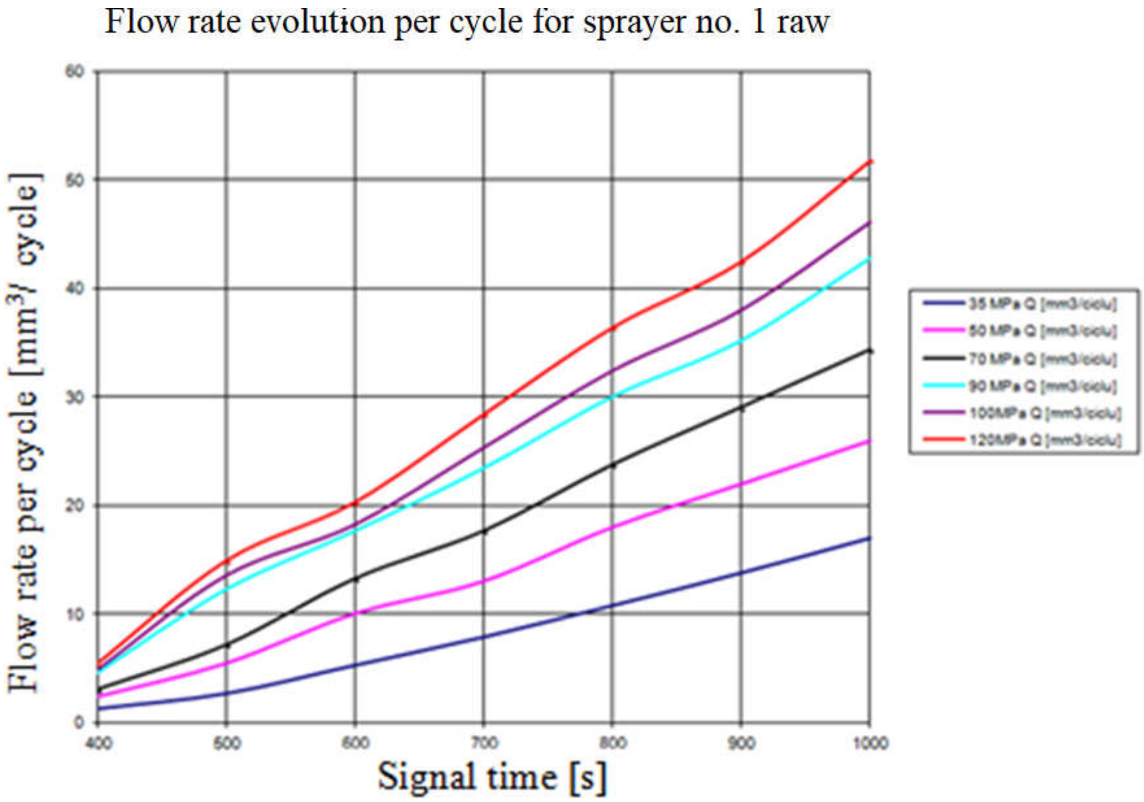


Figure 7.7. Injection characteristic for sprayer 1 raw

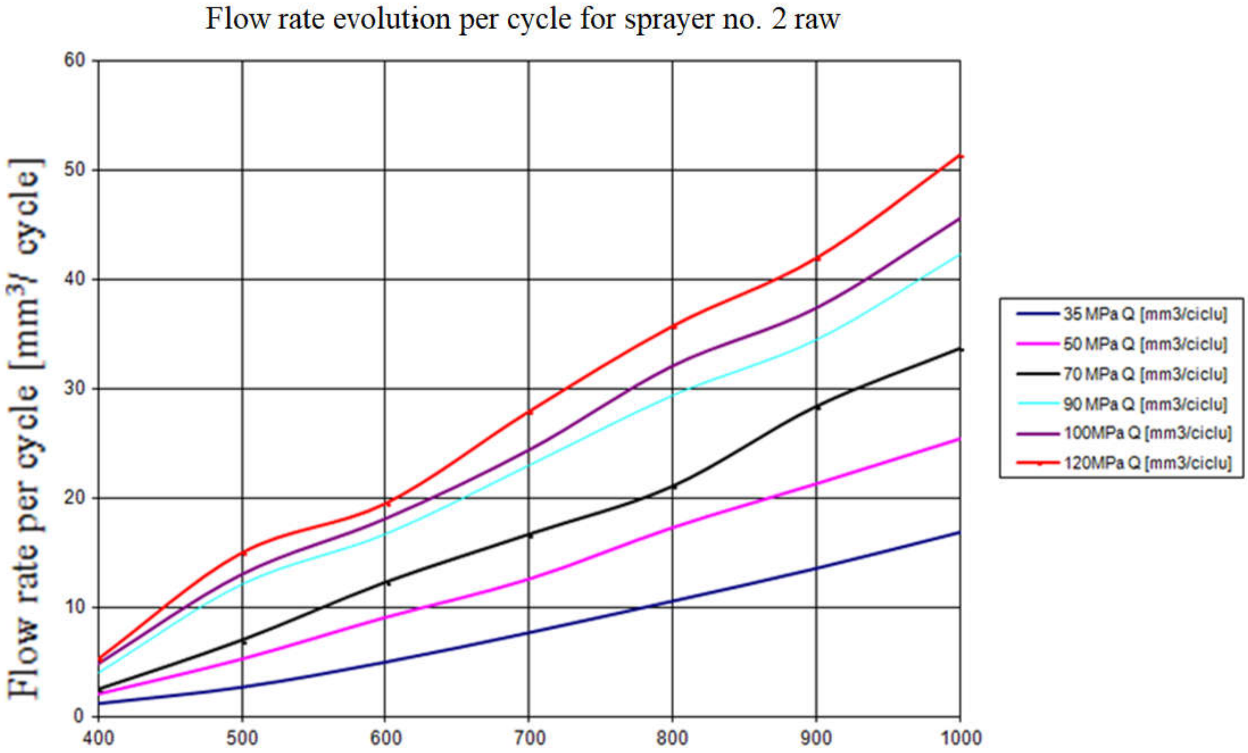


Figure 7.8. Injection characteristic for sprayer 2 raw

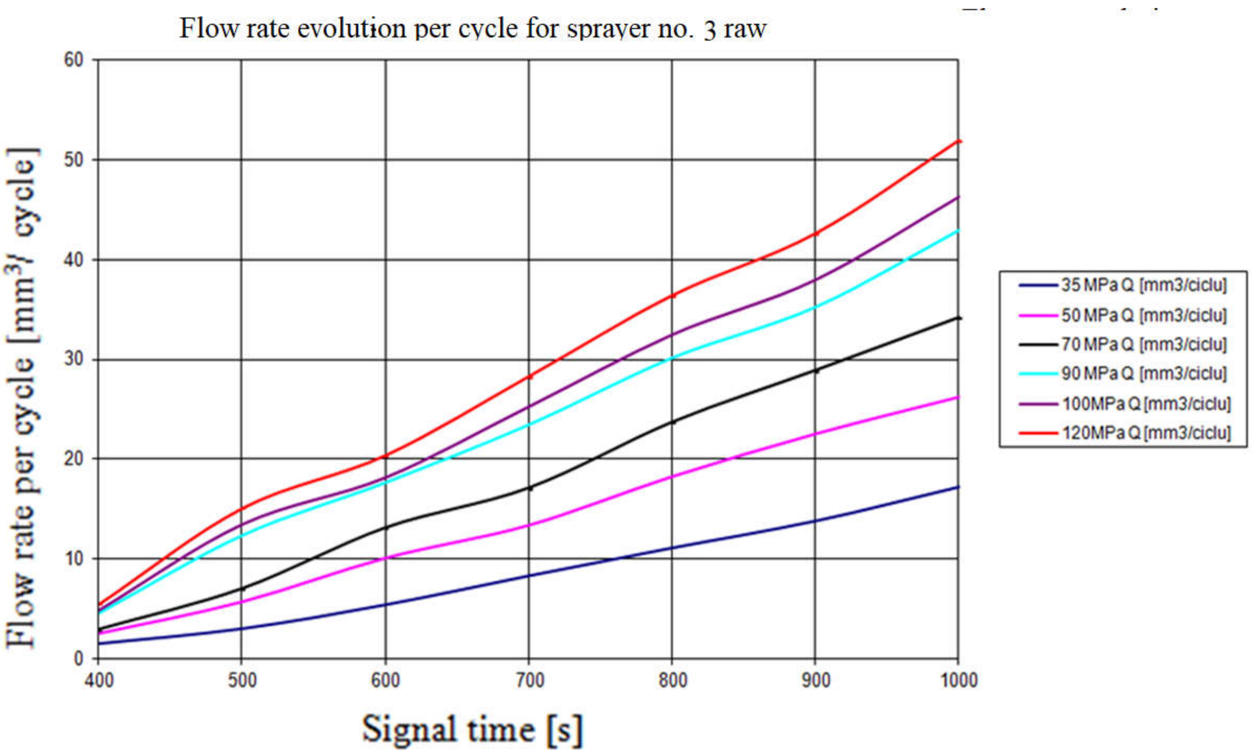


Figure 7.9. Injection characteristic for sprayer 3 raw

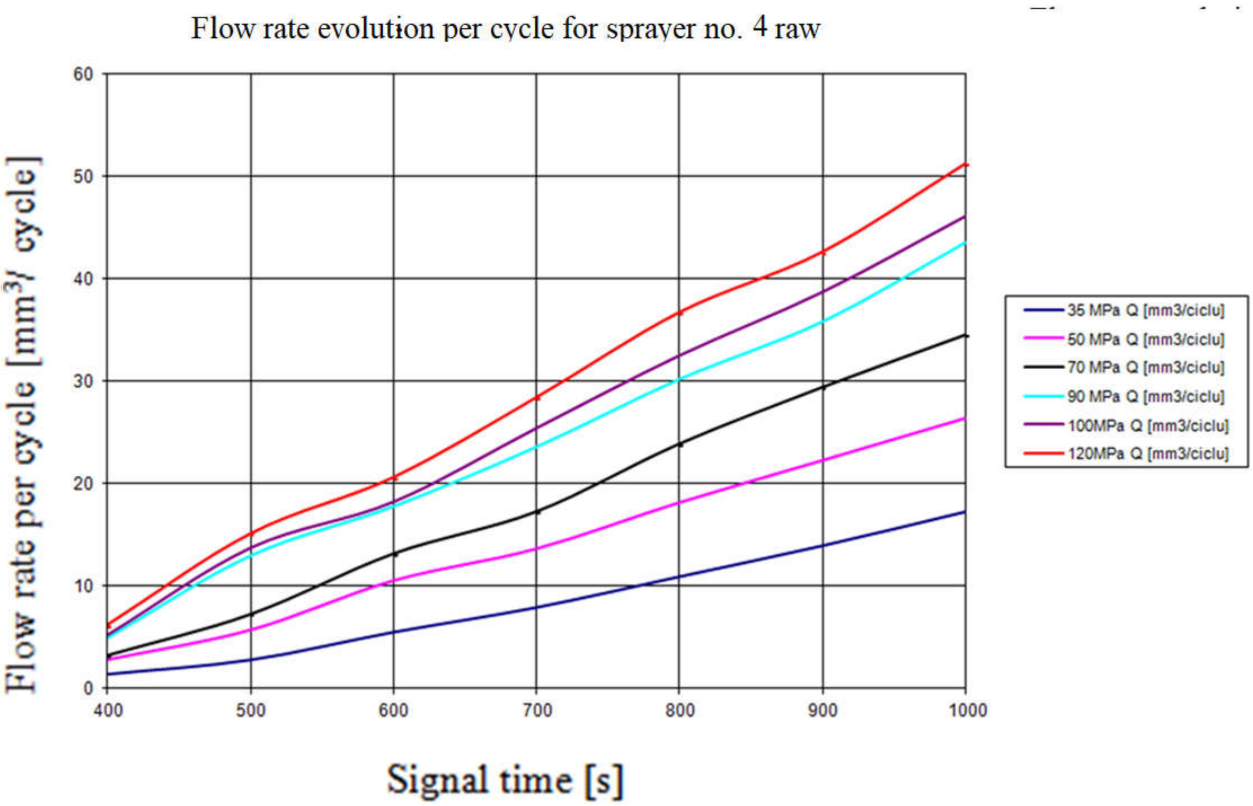


Figure 7.10. Injection characteristic for sprayer 4 raw

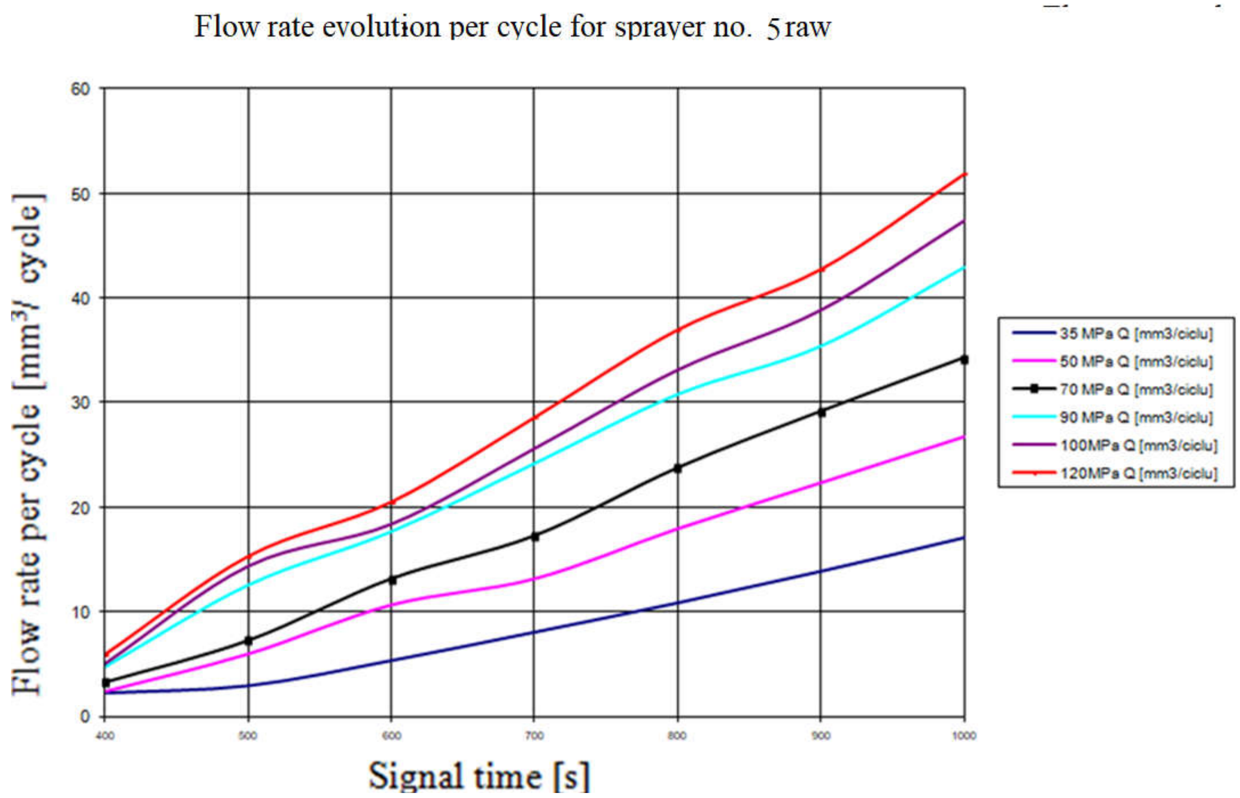


Figure 7.11. Injection characteristic for sprayer 5 raw

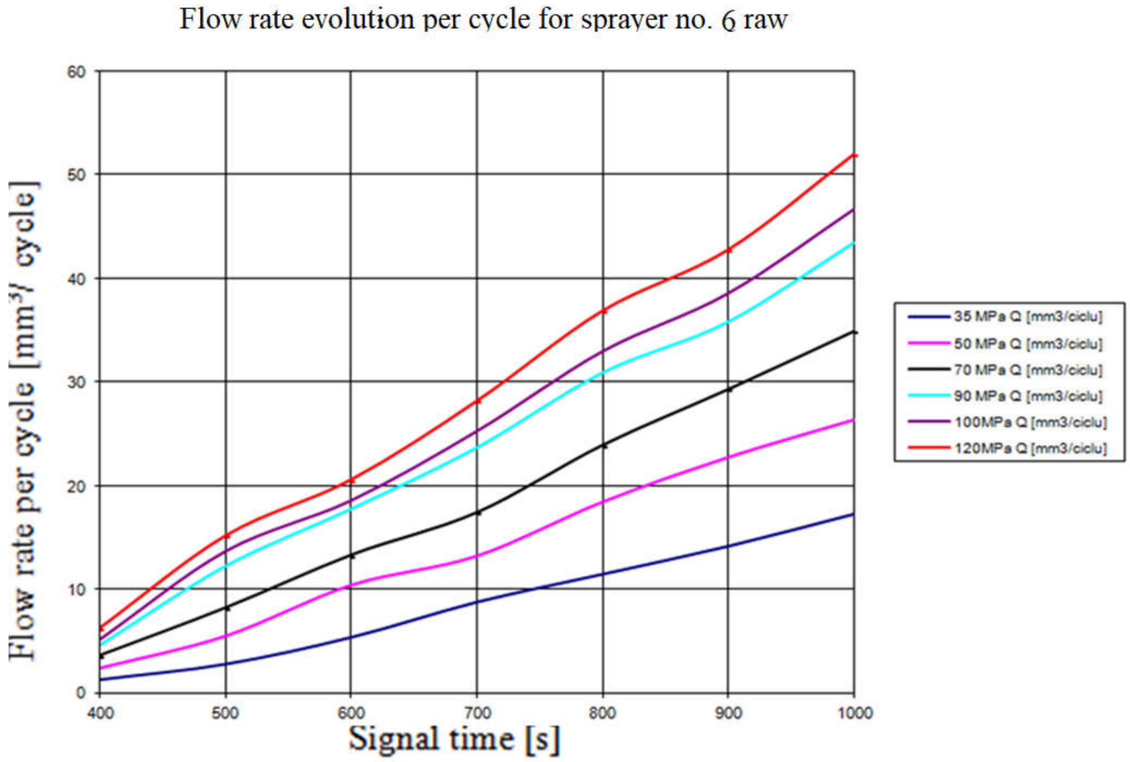


Figure 7.12. Injection characteristic for sprayer 6 raw

The results obtained for injection characteristics after processing are presented below.

Figures 7.13 ÷7.18 show the injection characteristics for sprayers 1 6, processed. For all samples, the signal duration was: 400, 500, 600, 700, 800, 900 and 1000 μs, and the pressures in the feed ramp were: 35, 50, 70, 90, 100 and 120 MPa..

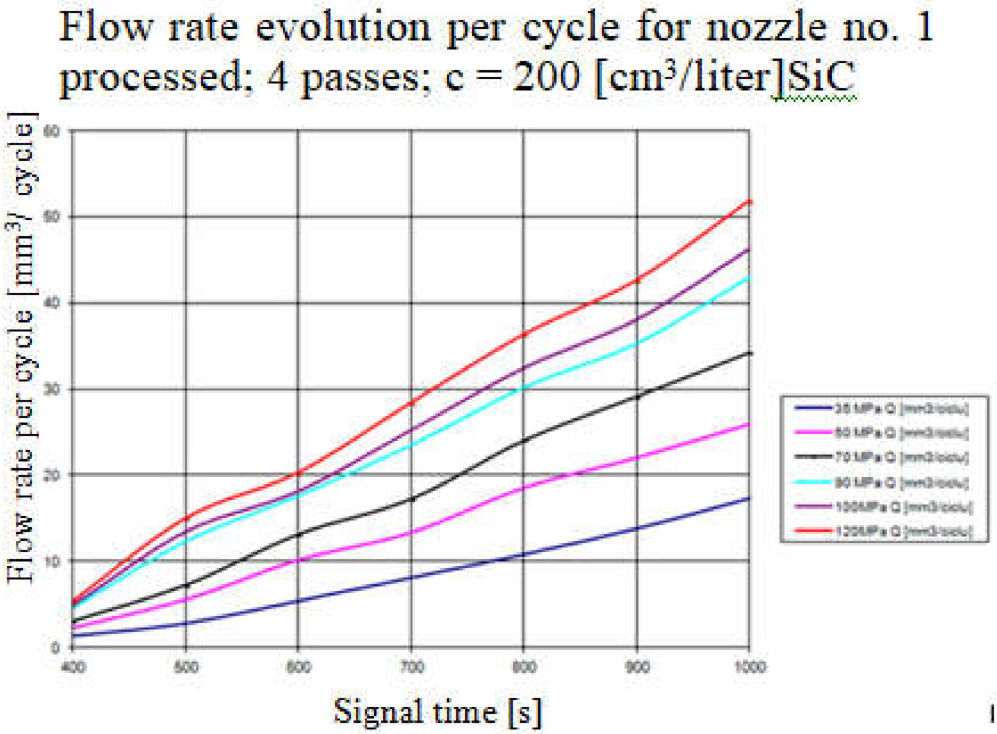


Figure 7.13. Injection characteristic for No.1 machined sprayer: 4 passes

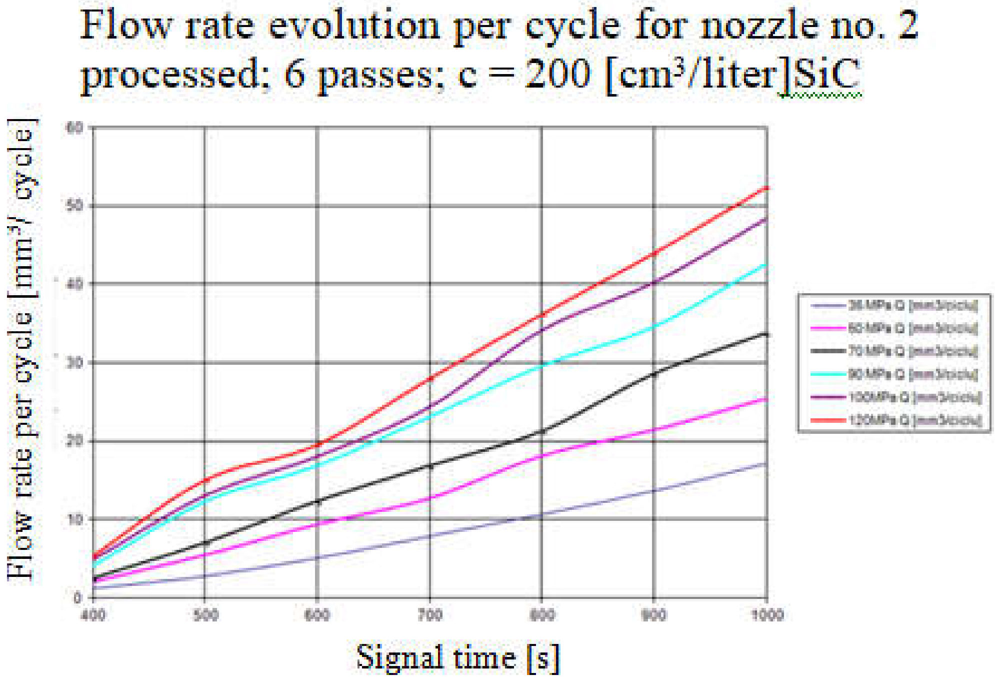


Figure 7.14. Injection characteristic for No.2 machined sprayer: 6 passes

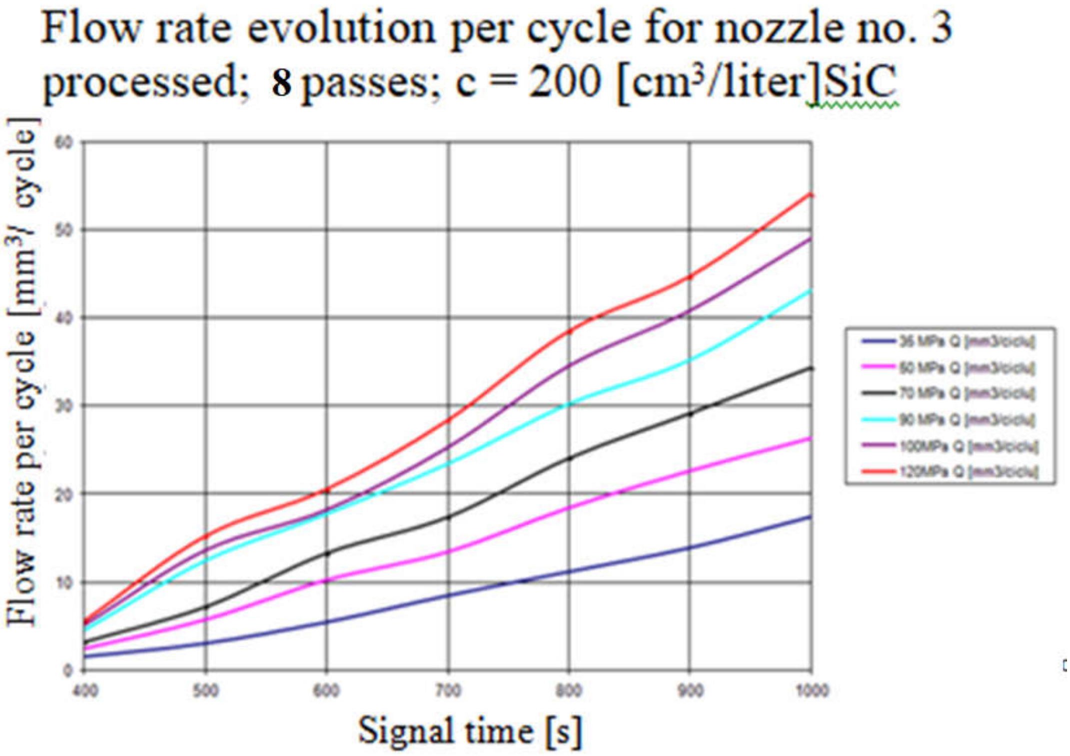


Figure 7.14. Injection characteristic for No.3 machined sprayer: 8 passes

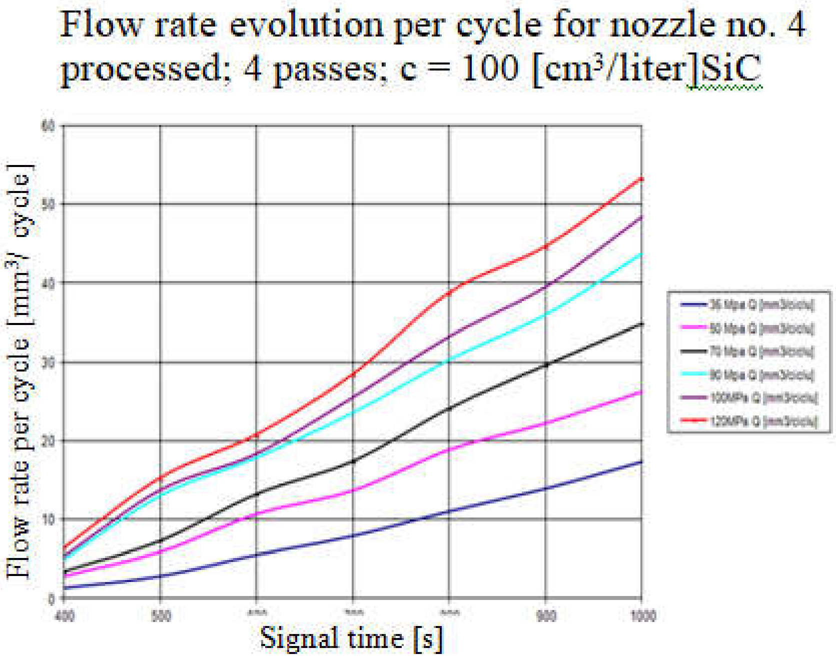


Figure 7.16. Injection characteristic for No.4 machined sprayer: 4 passes

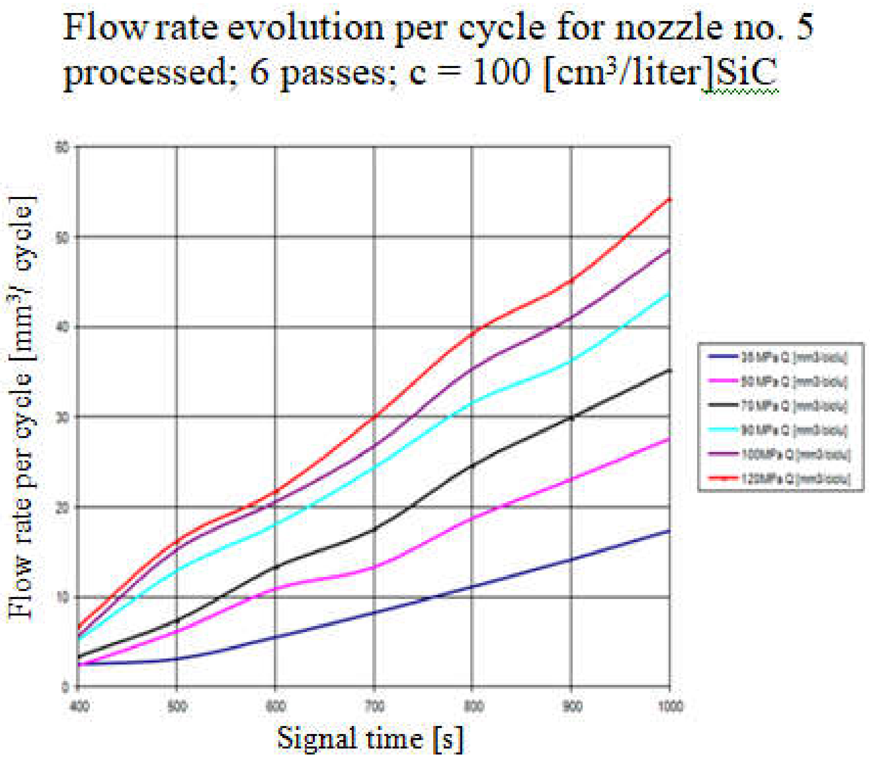

Flow rate evolution per cycle for nozzle no. 5 processed; 6 passes; c = 100 [cm³/liter]SiC

Figure 7.17. Injection characteristic for No.5 machined sprayer: 6 passes

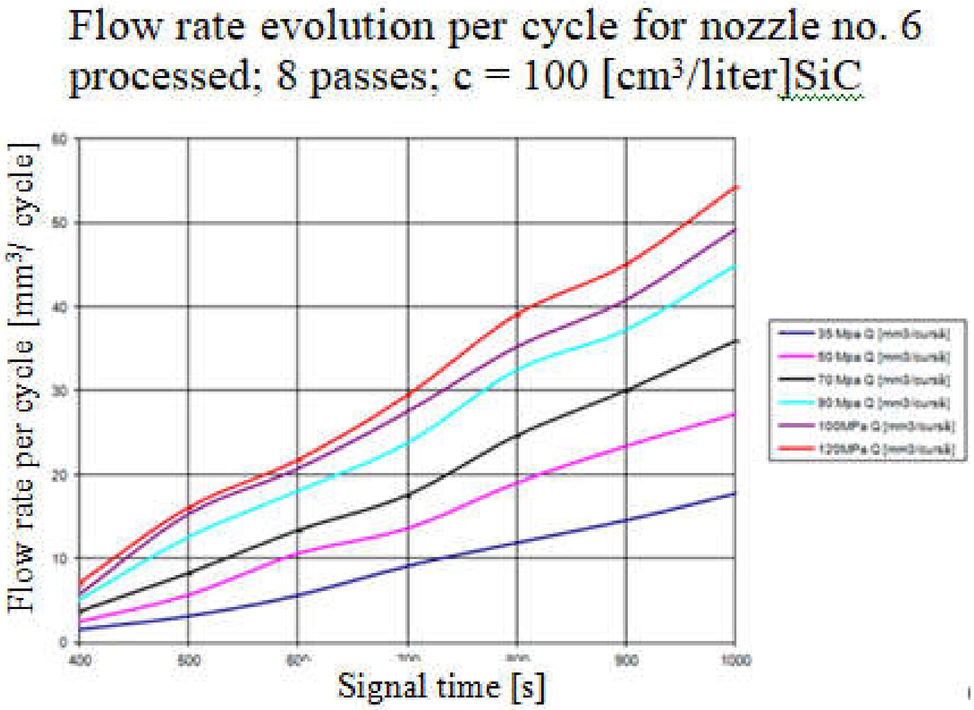

Flow rate evolution per cycle for nozzle no. 6 processed; 8 passes; c = 100 [cm³/liter]SiC

Figure 7.18. Injection characteristic for No.6 machined sprayer: 8 passes

For the analysis of the flow variation between the unprocessed and the processed sprayers, respectively for the analysis of the hydroabrasive processing of the sprayers under the conditions established in the experiment plan, the results presented in table 7.4 were obtained.

Table 7.4. Percentage values of (Qp/Qnp)max ratio [%] for the six sprayers

	Pressure p[MPa]					
Sprey	35	50	70	90	100	120
P1	3,704	3,704	3,333	2,222	4,167	1,852
P2	3,704	4,624	4,000	2,500	7,754	5,012
P3	6,667	4,372	6,667	2,222	7,632	5,769
P4	7,143	4,420	6,061	2,041	5,206	5,722
P5	8,696	3,889	3,361	8,333	11,413	13,559
P6	15,385	4,167	3,347	8,511	11,679	12,698

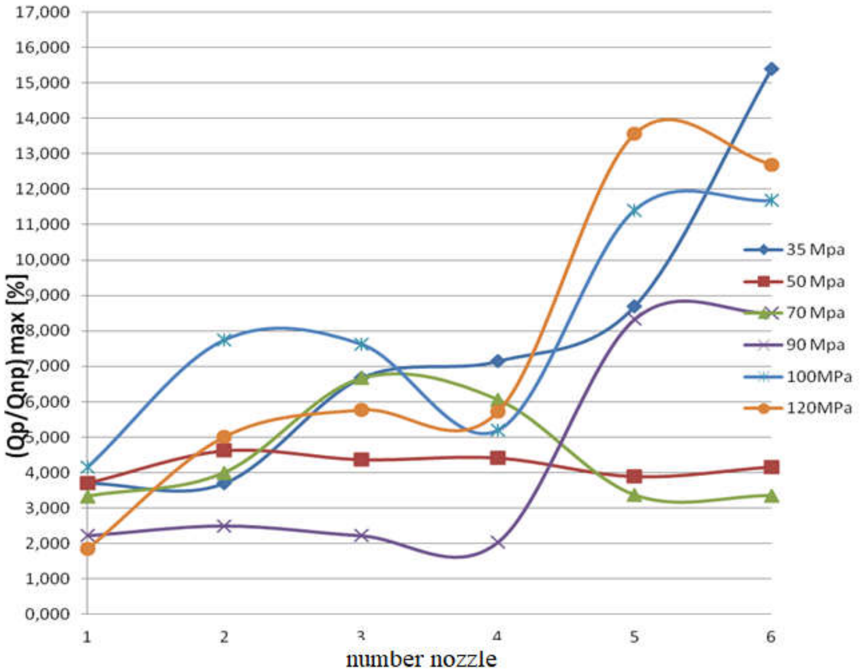


Figure 7.19. Plot of the variation of the percentage ratio of the maximum flow rate of preprocessed sprayers in relation to the maximum flow rate of the raw sprayer

From the analysis of the plot of variation, figure 7.19, of the percentage ratio of the maximum flow rate of the machined sprayers in relation to the maximum flow rate of the non-machined sprayers, it is found that the number 5 sprayer has a superior injection characteristic compared to the other machined sprayers. It should be noted that this ratio expresses the effect of rounding the inlet edge of the injection nozzle.

In conclusion, by processing with an abrasive fluid with a suspended abrasive concentration of 100 cm^3/liter and 5 passes, the best injection characteristic is obtained, which implies superior flow characteristics, respectively the improvement of the operating performance of the thermal engines.

For the analysis of the inner surfaces of the samples resulting from the experiment, it was necessary to section the injection sprayers on the axis of symmetry of the flow channel of the abrasive fluid. For sectioning, the EWAG type WS11SP tool sharpening, figure 7.20 and cutting machine and a CBN disc, (borazon), type B54, (granulation 54 μm) were used.

a) b) c) d)

Figure 7.20. EWAG type WS11SP tool sharpening and cutting machine: a), c) - overview; b) - vise-type fixing device; d) - borazone disk

The WS11SP sharpening machine is made up of the following important components: command and control panel, micrometer to be able to grind and process small parts, workpiece fixing mechanism, tool holder device, belt transmission, electric drive motor, cooling system and chip suction device.

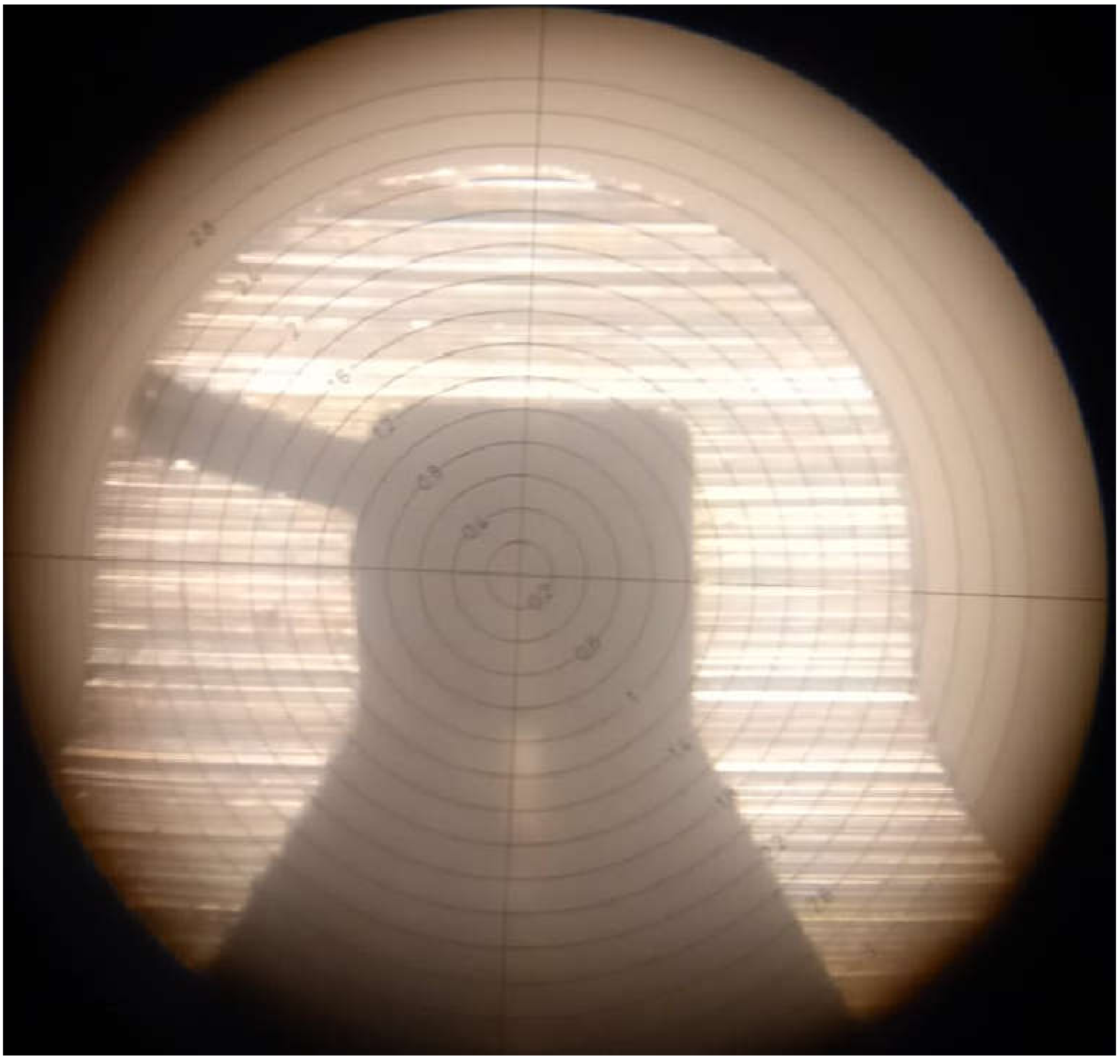


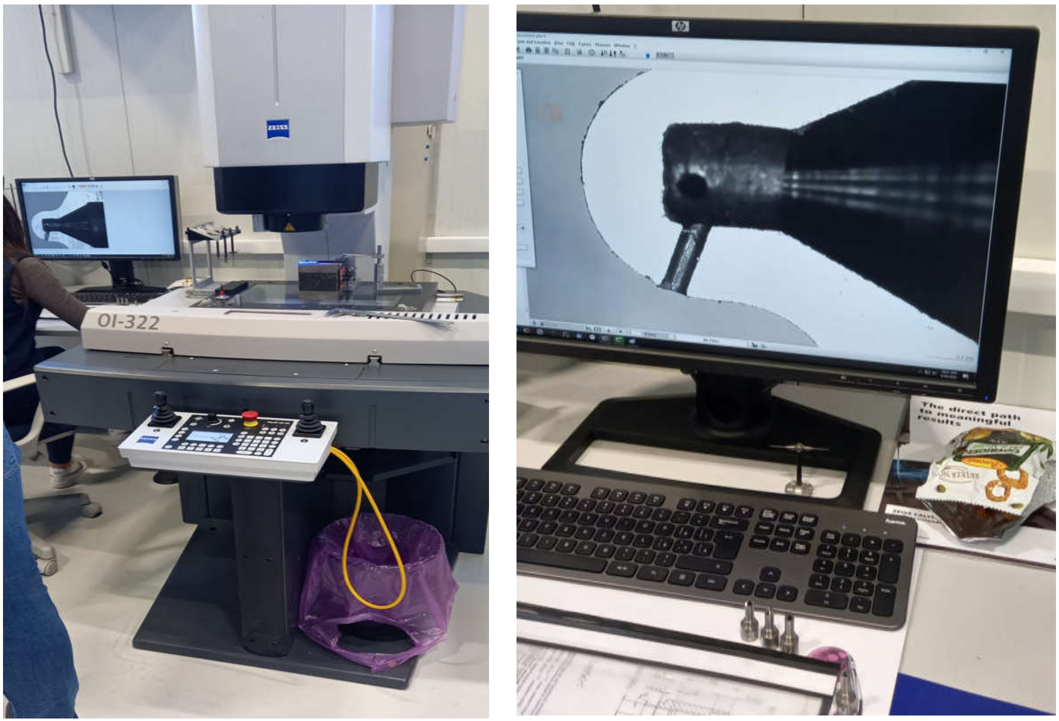
Figure 7.21. Image of the injection nozzle section on the axis of symmetry of the spray hole

It should be noted that sectioning on the axis of symmetry is difficult due to the fact that the flow holes of the sprayers are not in the plane of symmetry of the sprayer body, they are tilted by several degrees to create a certain turbulence of the sprayed fuel jet in combustion chamber.

Sectional sprayers with this type of machine are shown in figure 7.22.

Figure 7.22. Sectional injection sprayers in the area of the spray channel

After the sectioning operation, the spray channel surfaces were analyzed using the ZEISS CALYPSO digital multisensor and coordinate measuring device, figure 7.23. With this measuring device, measurements can be made easily, accurately and quickly.



a) b)

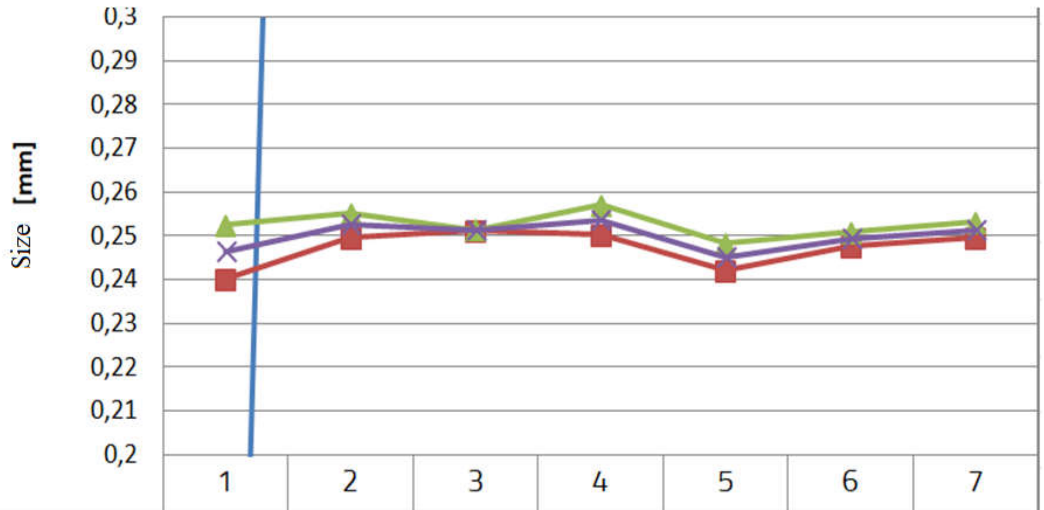
Figure 7.23. The ZEISS CALYPSO multisensor measuring device: a) - device overview; b) - data processing unit

Following the measurements, the results presented in table 7.5 were obtained.

Table 7.5. Minimum/maximum flow orifice diameter variation for the six sprayers

Using the sprayer	Abrasive concentration used [dm^3/liter]	No. passes for abrasive machining	The inside diameter of the hole [mm]	The outside diameter of the hole [mm]	The average diameter of the hole [mm]
N (raw)			0,2402	0,2525	0,24635
1	0,2	4	0,2497	0,2553	0,2525
2	0,2	6	0,2512	0,2514	0,2513
3	0,2	8	0,2503	0,2571	0,2537
4	0,1	4	0,2422	0,2482	0,2452
5	0,1	6	0,2477	0,251	0,24935
6	0,1	8	0,2496	0,2531	0,25135

From the dimensional analysis of the flow hole of the sprayers, after processing, it is found that the average diameter of the hole increases with the increase in the concentration of abrasive in suspension, as well as with the number of passes of the abrasive fluid through the hole to be processed, (figure 7.24).



	1	2	3	4	5	6	7
Number the nozzle	N	1	2	3	4	5	6
Inner diameter [mm]	0,2402	0,2497	0,2512	0,2503	0,2422	0,2477	0,2496
External diameter [mm]	0,2525	0,2553	0,2514	0,2571	0,2482	0,251	0,2531
Average diameter [mm]	0,24635	0,2525	0,2513	0,2537	0,2452	0,24935	0,25135

Figure 7.24. The plot of the variation of the diameter of the flow holes of the injection nozzles

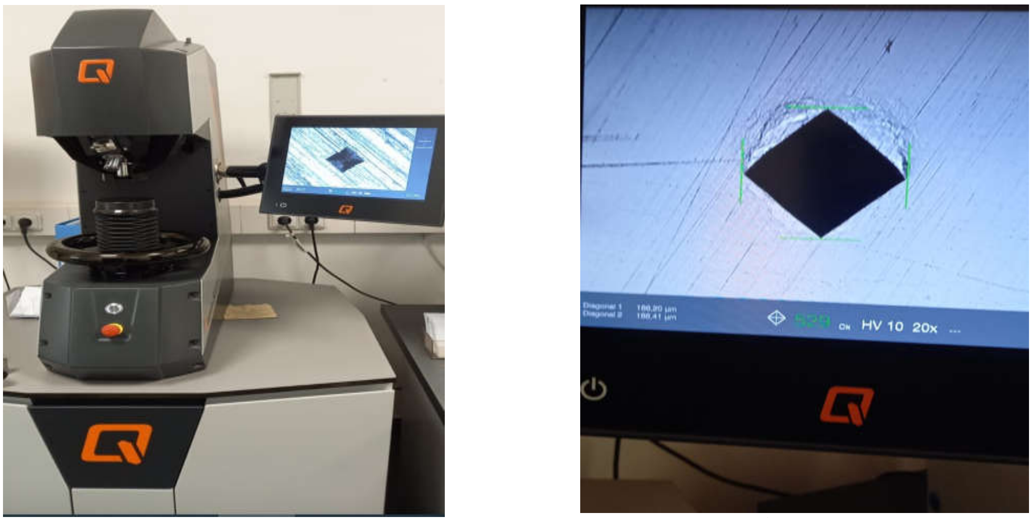
After sectioning the sprayers, the hardness was measured. To measure the hardness, the FM-700 type hardness tester was used (figure 7.25).

After measuring the hardness of the blank atomizer we found that the hardness of the fuel atomizer has a hardness of 66HRC (in the area of the cemented and nitrided layer).

a) b)

Figure 7.32. Tester FM-700 for measuring hardness: a) - general presentation of the tester;b) – the digital display of the measured hardnes

Considering that the hardness measurement in the area of the flow hole of the sprayer cannot be performed with this type of tester (the sprayer having a small microchannel size ϕ = 0.24 mm), we measured the hardness with a digital tester for measuring the hardness model Qualitest presented in figure 7.26.



a) b)

Figure 7.26. Digital hardness tester model Q: a) tester overview; b) measuring the hardness of the flow hole of the sprayer

The Qualitest model digital hardness tester has a resolution of 0.0625 μm and uses the four-point measurement method (two-diagonal measurement), x100 and x400 magnification ratio. After the measurement, it is observed that the hardness is 529 HV, (figure 7.33,b), equivalent to 51HRC, [AST2019].

After measuring the hardness of the control sprayer (with intermediate treatment) in the area of the microchannel, measurements were made to determine the surface roughness using the Mahr brand Mar Surf SD26 roughness meter with a PHT 6-350 probe, to study the flow surface of the fluid for the six sprayers processed and one unprocessed, obtaining the results presented in table 7.6.

Table 7.6 shows the roughness of the inner surfaces of the flow holes of the fuel injectors.

Table 7.6. The distribution of surface roughnesses of the sprayers used in the experiment

	Spray number	N	1	2	3	4	5	6
Roughness [μm]	Ra	0,272	0,261	0,232	0,211	0,204	0,185	0,176
	Rz	1,5626	1,701	1,167	1,067	0,267	1,095	0,981

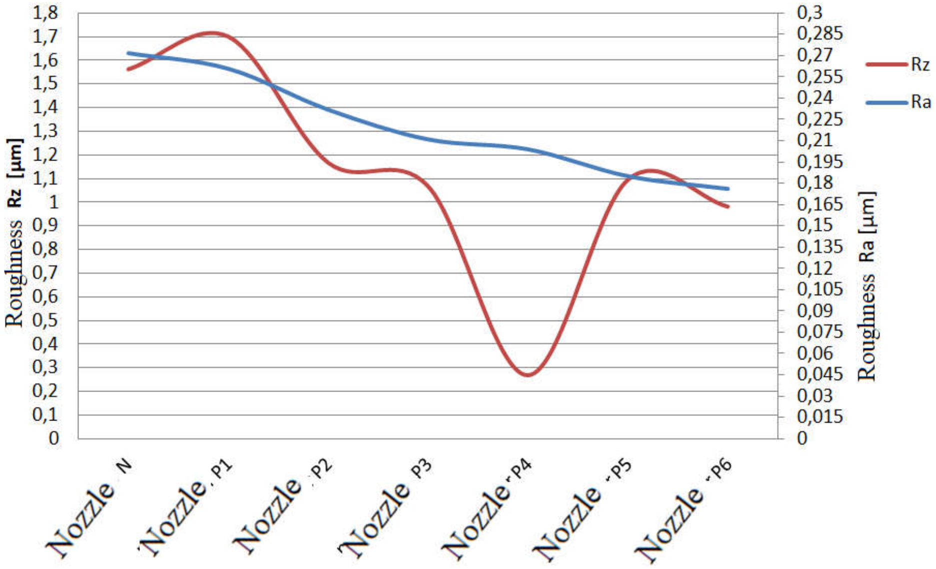


Figure 7.27. The variation graph of the roughness Ra, (arithmetic mean deviation of the profile), and Rz, (the mean height of the irregularities)

From the analysis of the variation graph of the surface roughness of the sprayer holes, figure 7.27, it is observed that the surface roughness Ra decreases with the decrease in the concentration of the abrasive and with the increase in the number of passes through the holes due to the fact that the particles are rounded with the increase in the period of use.

Next, measurements were made to determine the roundness of the entrance edge in the injection sprayer hole using the LEICA microscope, figure 7.28.

Figure 7.28. LEICA EMSPIRA3 microscope

Following the measurements, the following results were obtained, which are presented in table 7.7:

Table 7.7. The value of the connection radius of the injector sprayer hole

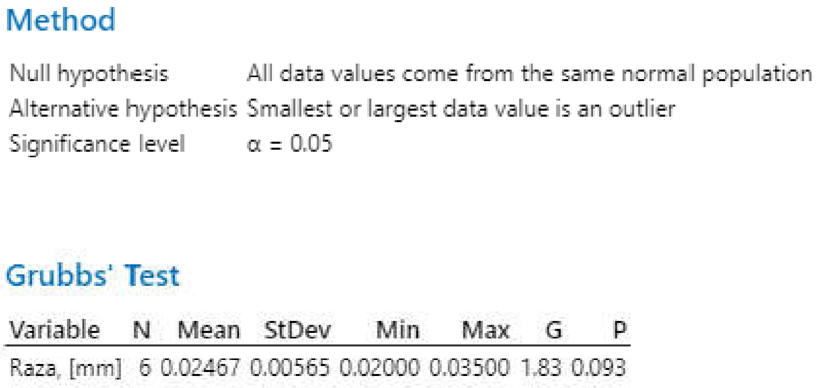
Spray number	N	1	2	3	4	5	6
Abrasive concentration [dm3/liter]	-	0,2	0,2	0,2	0,1	0,1	0,1
Number of passes	-	4	6	8	4	6	8
Range value [mm]	0,015	0,02	0,025	0,035	0,02	0,022	0.026

From the analysis of the values in table 7.24, it can be seen that as the concentration of the abrasive increases, respectively the number of passes of the abrasive fluid, the radius of rounding also increases, which is beneficial for the flow of the fluid - the effect of the appearance of cavitation is reduced. It should be noted that the rounding in the table is average because there is some measurement error in the measurements due to the unevenness of the cut surface.

After conducting experimental research and determining the values of the connection radius resulting from abrasive flux processing, the data obtained using the multiple linear regression method were processed with the aim of qualitatively expressing the relationship between:

$$Radius = f(Volume\ fraction, Abrasive\ flow\ volume)$$

In a first step, an outlier elimination test (Grubbs test) was applied to the experimental data in order to identify whether the experimental results are affected by measurement errors. Minitabul was also used in this case, with a significance level α=0.05.



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Method

Null hypothesis        All data values come from the same normal population
Alternative hypothesis Smallest or largest data value is an outlier
Significance level     α = 0.05


Grubbs' Test

Variable    N  Mean    StDev   Min     Max     G    P
Raza, [mm]  6  0.02467 0.00565 0.02000 0.03500 1.83 0.093
```

* NOTE * There are no outliers at the 5% significance level.

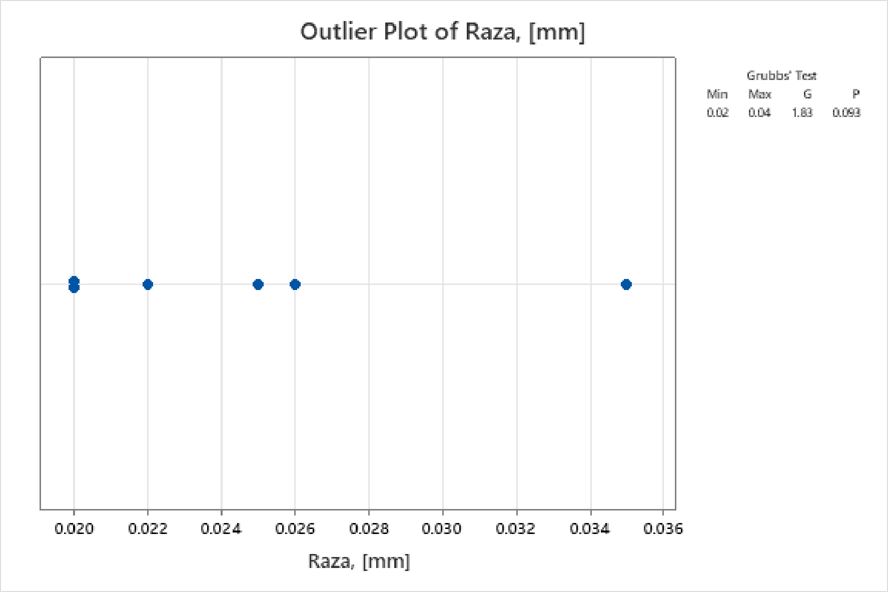

Figure 7.29. Graphical distribution of the experimental point distribution of the radius of rounding of the edge of the fuel injector hole

The conclusion is that the experimental data are not affected by measurement errors.

The second stage of processing consists in performing a test of agreement of the experimental data with the normal distribution model. In this case, the Anderson-Darling test was used with a significance level of α=0.05.

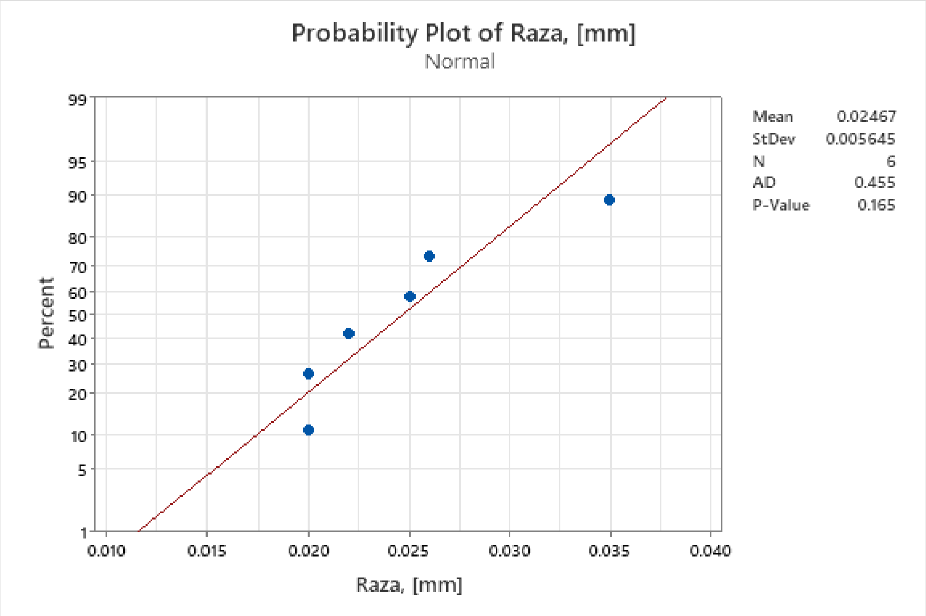

Figure 7.30. The normal probability network of the radius of gyration of the edge of the fuel spray nozzle

The purpose of applying this test is to check if the assumption of normality of the data used, which is the basis of the regression calculation, is met. The conclusion is that the radius values obtained are normally distributed with the mean:

$$\mu = 0{,}02467$$

and the mean squared deviation:

$$\sigma = 0{,}005645.$$

The multiple linear regression relationship obtained using Minitab is:

```
Regression Equation

Raza, [mm] = 0.00292 + 0.000400 Fracția de volum, [%] + 0.002625 Volum, [l]
```

The value of the coefficient of determination:

$$R^2 = 84{,}26\ [\%]$$

indicates that the previous equation explains 84.26% of the variability of the analyzed process. The remaining 15.74% is due to the influence of factors that were not considered in the analysis performed.

As the weight of the two independent factors considered:

- the volume of abrasive flux used in processing has a weight of 69.19%, and
- the volume fraction has a weight of 15.06 %.

7.3. Conclusions related to the experimental researches of hydroabrasive machining with ultrasonically assisted abrasive flow

The experimental research was carried out in three stages:

(a) In the first stage, the hydroabrasive machining facility with ultrasonic assisted flow was designed and built.

The use of a hydraulic system to create the pressure required to perform the experimental tests in the experimental device can lead to the test parameters that are easy to control and realize the easy adjustment of pressure and flow, which meet the different requirements for pressure and flow in the comparative test. . At the same time, the hydraulic system is easy to control and provides protection against overload, complying with labor protection norms, performing the tests safely.

This designed and built test device meets the strength requirements of materials. All the components can withstand an operating pressure of over 200 bars, a fact proven by the technical characteristics of the components, being able to satisfy the requirements necessary to carry out the experiments and complete them successfully.

(b) In the second stage, the experimental researches were carried out according to the established experimental plan.

During this stage, the flow holes of the injection sprayers were processed, their tests were carried out on the stand to check and test injectors, the sprayers were sectioned on the axis of symmetry of the sprayer hole, the geometry of the flow holes of the sprayers was established injector and hardness tests of the atomizers were performed.

Since the machined parts have complex geometries and small dimensions for diagnosis, state-of-the-art devices and high-performance devices were used, as well as the sectioning of samples in the area of the sprayer holes to check the condition of the surfaces after processing.

(c) In the third stage, the collection and interpretation of the results obtained from the experimental tests was carried out.

Machining efficiency is influenced by the pressure and average flow rate of the abrasive fluid.

The reduction of the negative effects of the cavitation that occurs due to the turbulence, is achieved by rounding the entrance edge in the injection sprayer hole, a fact achieved by this hydroabrasive processing process and validated by the dynamic characteristics made at the stand to check and test injectors.

At this stage, the conclusions of the theoretical research were validated.

PART IV - CONCLUSIONS AND FINAL FINDINGS. PERSONAL CONTRIBUTIONS. FUTURE DIRECTIONS OF RESEARCH. DISSEMINATION OF RESEARCH RESULTS

Chapter 8. Conclusions and final findings

In the framework of the Doctoral Thesis, "Research on the improvement of the manufacture of injection nozzles in internal combustion engines", a topic that has not been explored in detail was studied, namely the processing of the flow holes of the injection nozzles using hydroabrasive machining processes with ultrasonically assisted abrasive flow, which is of great interest in this field, taking into account that the current trend is for the optimization of manufacturing processes in order to obtain high performances, in particular for the reduction of pollution due to the combustion of liquid fuels. There are also insufficient data on the construction and monitoring of functional and constructive parameters of hydroabrasive processing facilities.

Following the analysis of the state of recent research in this field, as well as the theoretical and experimental research undertaken by the author, the following general conclusions emerge:

- the hydroerosion manufacturing process plays a vital role in the automotive industry and recent studies show that finishing operations in the last stage represent approximately 15% of the manufacturing cost;

- physical phenomena, such as particle agglomeration, their collision, geometric shape and surface roughness can be relevant and inevitably introduce a certain degree of uncertainty thus limiting the numerical simulation, to some extent in its accuracy. However, the numerical simulation in this study was used as a tool for the identification and analysis of turbulence phenomena, which is in most cases sufficient for the design and optimization of the hydroerosion manufacturing process;

- the process parameters, including the number of cycles, the temperature of the medium and the extrusion pressure, the rheological properties, the concentration of the abrasive medium are critical factors, with significant importance in surface finishing;

- the increase in carrier fluid/abrasive concentration ratios led to a reduction in the degree of finishing, having a good polishing effect for 1/10 concentration ratios;

- the surface roughness of the flow hole of the sprayer decreases rapidly after four processing cycles, a fact that determines the reduction of finishing costs;

- erosion is a very complex field, because the mechanism of erosion depends in particular on the combination of the erosion mechanism, the properties and impact parameters associated with the abrasive particles and the dynamic and structural properties of the material of the part being processed;

- to obtain reliable results, the experiments must be evaluated through repeatability, based on comparative analyses;

- the diagnostic and analysis methods of the processed surface represent an essential component of the experimental analysis. State-of-the-art diagnostic and inspection methods were used in this work to quantitatively and qualitatively evaluate the hydroabrasive manufacturing process;

- erosive wear was analyzed through the changes in the surface profile, because the mass loss estimates do not provide information about the quality of the surface after the processing process;

- erosion is measured by surface profile changes, as mass loss estimates do not provide qualitative information about local wear;

- from the analysis of the simulation and experimental results, it is found that the processing technology with ultrasonically assisted abrasive flow is an effective method of finishing the surfaces, especially of rounding the entrance edges of the injection sprayer holes, thus obtaining an improvement of the flow of fuel through the sprayer holes and the reduction of noxes;

- the analysis of the results obtained following a plan of experiments allowed obtaining the dependencies that exist between the factors that influence the results obtained and the processing.

Chapter 9. Personal contributions. Future research directions. Dissemination of research results

9.1. Personal contributions

The realization of the research specific to the doctoral thesis was supported by a series of personal contributions of the author both theoretically and experimentally in the field of hydroabrasive processing with ultrasonically assisted abrasive flow as follows:

- carrying out a critical study of research in the field of injection sprayer manufacturing;
- design of a hydroabrasive processing installation with ultrasonically assisted abrasive flow;
- realization of the hydroabrasive processing plant:
  - identifying and purchasing the necessary components that are reliable and meet the technical requirements;
  - assembling the components according to the functional diagram;
  - commissioning of the hydroabrasive processing plant;
  - optimization of the main functional parameters of the installation based on operational tests;
- designing and making the necessary parts for the assembly of the injection sprayers on the processing stand, as well as on the injector checking stand;
- design and manufacture of injector nozzle mounting nuts on Delphi injectors;
- designing and making modifications to those injection sprayers;
- modeling and simulating the flow of the abrasive fluid through the holes of the injection sprayers respecting the experimental plan;
- carrying out experimental tests on the hydroabrasive processing stand (installation);
- sectioning of the experimental samples (injection sprayers on the axis of symmetry of the fluid flow holes);
- comparative analysis of functional and constructive characteristics of injection sprayers after processing;
- experimental determination of the hardness of sprayers;
- experimental determination of the parameters of the machined surface of the sprayers used in the experiment;
- analysis and validation of theoretically obtained results through experimental results.

9.2. Future research directions

The study of hydroabrasive machining with ultrasonically assisted abrasive flow led to a better understanding of the mechanisms involved in the machining process and helped to optimize this process. The characteristics and behavior of various major measures of machining performance have been analyzed in this paper.

Taking into account the research carried out in this study, the following research directions can be formulated:

optimization of mathematical modeling with the objective of minimizing production cost;

study of the feasibility of implementing a monitoring system for size distribution during the processing process and automatic addition of particles for a uniform distribution;

investigating the drop in oil viscosity after a long period of use;

theoretical and experimental studies to determine the combination of oil viscosity and particle size range to increase the efficiency of the processing process. The results can be used to define process parameters as well as abrasive particle addition intervals and carrier fluid addition or replacement.

9.3. Dissemination of research results

The dissemination of the results obtained during the research was carried out by publishing a number of six scientific articles, as first author and sole author, as follows:

-an article presented at the international conference MSE 2021, whose papers are indexed CAS, Clarivate Analytics (Web of Science - WoS), [POM2021];

-five articles published in journals Indexed in BDI: [POP2021], [POP2022], [POM2023a], [POM2023b], [POP2023].

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