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PULSED GASEOUS DETONATION GUNS FOR COATING DEPOSITION

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ABSTRACT

This paper is devoted to recent accomplishments in basic and applied research on gaseous detonation guns for thermal spraying. The conditions of processing powder materials are governed by the thermal, velocity, and chemical relaxation of particles in a high-temperature two-phase pulsed stream generated at every working cycle of the gaseous detonation guns (GDG). The relaxation of particles is conditioned by the parameters of the entire system under consideration and depends not only on the energy of a single pulse and the parameters of the high-temperature gaseous medium, but also on the spatial arrangement of a fresh gas charge and a single dose (metered amount) of powder. The classification and design concepts of detonation guns are discussed. The possible versions of D-guns operation cycle are described. The better understandings of knowledge of the involved phenomena are necessary for improvement of the design of gaseous detonations guns.

KEY WORDS

Coatings, Thermal spraying, Powder Particles, Particle Velocity, Particle Temperature, Gaseous Detonation Gun, Design Concepts, Operation Cycle, Detonation Wave.

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INTRODUCTION

In spite of competing processes (chemical vapor deposition (CVD), physical vapor deposition (PVD), *etc.*) and certain drawbacks, thermal spray process sales are increasing regularly (almost by 10% per year since 1990 [1]). The growth will probably continue, because spraying techniques are relatively harmless to the environment and the full potential of thermal spraying as an alternative to more conventional coating techniques (*e.g.,* hard chromium) for processing "multi-materials" or for free forming and repairs is still undiscovered. However, this development could be enhanced with increased quality of coatings and process reliability. It demands improved process understanding and on-line control with a real time closed-loop control. Decades of research and development in thermal spray (TS) processes have exposed that higher performance and lifetime coatings can be produced if the feedstock particles are accelerated to a high velocity and heated prior to impact on the substrate to be coated [1].

Almost in parallel to plasma spraying, Union Carbide (now Praxair Surface Technologies, Inc., Indianapolis. IN) marketed the trademarked D-Gun producing premium coatings, especially metallic and cermet ones, which have long been the goal of all other coating processes, *i.e.,* higher density, improved corrosion barrier, higher hardness, better wear resistance, higher bonding and cohesive strength, almost no oxidation, thicker coatings, and smoother as-sprayed surfaces. However, the detonation gun (D-Gun) process was available only as a service [1].

For a long time, D-Gun technology has been the reference standard in producing metallic and cermet coatings. However, as it was available only as a service, no research work was published on the process. With the transformations that occurred in the former USSR, Russian equipment and literature on the subject became available in the mid 1990s. Compared to high velocity oxy fuel spraying (HVOF) or plasma spray processes, much work, some of which is in progress, is necessary to better understand the phenomena of the D-gun process.

Historically, the two fundamental modes of combustion, namely flame and detonation, have found a wide variety of applications in human activities. It is a slow flame that has been extensively utilized in propulsion, power engineering, material science, and chemical technology, while detonations were used basically for military purposes. As the knowledge in detonation physics and chemistry is continuously advancing, one inevitably arrives at the time when this knowledge is to be used for constructive purposes as well to help humanity at large. Detonation is a very attractive phenomenon from the viewpoint of the thermodynamic efficiency of chemical energy conversion into thermal and kinetic energy. Once this advantage of detonation is capitalized properly, considerable benefits are expected to be achieved in terms of fuel consumption, manufacturing and operational costs, pollutant emissions, etc. [2].

This paper is a short report of the present understanding and knowledge how to design the gaseous detonation guns for thermal spraying.

THE OPERATION CYCLE OF DETONATION GUN

The detonation-spraying technique is cyclic. In a GDG, detonation is initiated in a barrel that serves as the detonation chamber (DC). The detonation wave rapidly traverses the chamber resulting in a nearly constant-volume heat addition process that produces a high pressure in the combustor and provides the formation of high velocity impulse flow, which used for powder heating and acceleration.

The steps of an impulse burn-out of the combustible mixture and formation of an impulse heterogeneous stream are governing steps and depend greatly on the quality of barrel filling. Repetition of cycles causes the fresh charge to contain a certain amount of combustion products and powder from the preceding spraying cycle. The gases and powder, on the one hand, reduce the mass of a fresh charge and, on the other hand, adversely affect the processes of burn-out and formation of an impulse heterogeneous stream themselves. It is therefore natural to attempt to reduce the fraction of residual gases and powder in a fresh charge. Also the flow of a working medium (purging gas, fresh combustible mixture or gas suspension of the initial powder) has a limited time to overcome the resistance of inlet paths, to contact heated surfaces etc. All this changes the density of the working medium and hence also the mass of charge capable of filling a barrel of predetermined dimensions, the degree of barrel filling, the spatial distribution of fresh charge components in the barrel. The barrel-filling processes have been poorly studied.

After the barrel has been filled, an ignition source operates, installed in the combustion chamber, or in an ignition chamber or in the combustible mixture feed piping. The mixture ignites, a flame front emerges, and burn-out of the combustible mixture occurs accompanied by progressive acceleration of the flame until a stationary detonation mode arises. The pressure in the barrel during combustion rises and burn-out and is accompanied by ejection of incandescent combustion products jointly with suspended powder particles through the open end of the barrel. After the discharge, the pressure in the barrel first drops below atmospheric pressure (because of the inertia of the flow) and then equalizes. The combustion chamber is again filled with a fresh charge, and the process is repeated. Thus, vibration burning with discontinuous oscillations (relaxation or non-resonance burning) occurs in the barrel.

The regularities in the burn-out of the combustible mixture and in the outflow of combustion products from the barrel are the scientific fundamentals to be considered in an efficient development of spray-coating production processes. However, this step of the working cycle has not yet been studied sufficiently. The most urgent issues for further investigations should include the following: the effect of design characteristics and the geometric configuration of the barrel, ignition chamber and other pre-barrel spaces on the development and conditions of the combustible mixture burn-out, outflow of detonation products and heat exchange with the barrel walls; the composition and properties of combustion products and their change during mixture burn-out and gas outflow from the barrel; the optimization of the design characteristics of detonation-spraying plants to provide the most efficient conditions of combustible mixture burn-out and subsequent interaction of combustion products with the powder.

Some Gas Dynamic Characters of Detonation Spraying

The main possible schemes of sprayed powder distribution into barrel of detonation spray gun and appropriate regularities of powder particles interaction with detonation wave and concomitant gas flow were analyzed early [3-4]. The conformities of flowing of impulse high temperature stream with suspended powder particles inside barrel and its outflow from GDG barrel were viewed. The advantages and disadvantages of manners of initial powder disposition inside barrel before explosion of combustible mixture have important significance.

The technological criteria for preliminary choice of sprayed powder particles and powder cloud sizes were proposed. As one of technological characteristic of detonation spray coating could be the duration of impulse two phase jet interaction with sprayed surface. The possibility of mutual influence of sprayed particles onto physical-chemical interaction with sprayed surface was shown.

The strategy of calculation of velocity and traversing of powder particles, which introduced into low temperature flow of fresh gas entering to barrel in time of its filling, also was described. The means of control by initial powder cloud parameters, which determining the particles heating and movement and physical-chemical transformations of sprayed material in process of interaction with impulse high temperature flow of gaseous detonation products, are shown. It is established that main factors, which influencing on initial disposition of powder cloud into barrel, are velocity of fresh gas flow, time slots of timing diagram, relaxation time of powder particles in gas flow and initial velocity of powder particles in process of injection.

As result of generalization of theoretical research of physical processes during spraying, the structural scheme of complex mathematical modeling is proposed [5]. It is shown that outflow of powder cloud from barrel consists of two successive stages: (1) one-dimensional motion of dispersion mixture inside barrel; and (2) two- dimensional axisymmetric recession of powder cloud into environment. The developed mathematical model allows to determine the spatio-temporal parameters of sprayed particles flow as inside the barrel as between barrel exit and substrate, and also when the barrels with variable cross-sections are used. For computer realization of developed models the software is created, which include code for calculation of parameters of gaseous detonation waves, code for modeling heating and acceleration of powder particles, and editor of databases of properties of gases and powder materials. This software may be used independently for numerical experiment of processes of gaseous detonation spraying and process variables optimization, as could be integrated into expert systems and decision support systems.

Some results of modeling powder particles behavior depending on some spraying parameters are given at Figures 1 and 2 [5,6]. The discrepancy of experimental and calculation data is not more than 5% for particle velocity and 15% for particle temperature. Therefore, the given software may be used for computational investigation and selection of optimal process variables.

The Influence of Particle Velocity on Collision with Substrate

The thermal sprayed coatings could be formed from molten, fused and solid particles. The enhancement of impact velocity is resulted for more intensive as plastic deformation of substrate near surface layer and particles as mechanical activation of interacted materials. The main factors, which influenced on intensity of plastic deformation, are discussed. Chiefly the resistance for deformation of materials is determined as at solid state by their dynamic hardness and impact resistance as at liquid state by viscosity and impact resistance. The more likely for thermal spraying practice cases of particle-substrate collision are studied. It are: 1) impact of solid particles with plastic substrate at relatively low velocities; 2) impact of solid particles with plastic substrate at relatively high velocities; 3) impact of plastic or liquid (easy deformed) particles with hard substrate.

The mechanism of deformable particles collision is considered in detail [7]. The influence of particles velocity on main parameters of impact is analyzed. There are the three specific zones of sprayed particle-substrate contact. They are: 1) the central circumferential, which is subjected to exposure of as impact as forward pressure; 2) the intermediate ring shaped, which is subjected to exposure of as forward pressure as contact friction; 3) the peripheral ring shaped, which is subjected to exposure of contact friction. The analytic study of influence of particle velocity on its spreading onto hard substrate surface and extent of particles distortion is given. The character of stress distribution onto particle-substrate contact at different moments of collision was studied. The results of experimental study of collision of individual powder particles with solid surfaces during DGC spraying are given [8, 9].

Mechanism of Coatings Formation

One of the main purpose of this paper is to discuss the mechanism of adhesion formation between sprayed particles and solid surface in process of their high velocity collision up to 1000 m/s. It is possible to divide the collision of particles with substrate and the stress distribution on substrate surface in time of impact into three stages: stage of particle elastic deformation before splattering begins; stage of initial particle flattening; stage of particle flattening. The sources of mechanical activation of central zone as no more 2.5% of contact area are impact pressure and head pressure; the same of ring zone are head pressure, Relay waves and friction forces. The contact temperature between particle and substrate in time of impact is also a function of impact and head pressure and the heating of solid substrate by turbulent flow of the metal. An investigation was conducted to define the basic technological parameters of spraying that determine the energy state of particles and consequently the conditions of coating formation. The equation for adhesion strength as function of particle velocity and temperature was obtained.

GASEOUS DETONATION GUNS

The quality of detonation sprayed coatings depends in mane respects from design philosophy and functioning stability of used detonation gun equipment [10, 11]. A specific feature of operation of GDG consists in periodical sustained oscillations of the pressure, velocity, temperature, and acceleration, which arise inside the barrel and other structural elements of the GDG. The oscillations are not caused by external periodical effects and therefore belong to auto-oscillations. Like any auto-oscillatory system, the GDG consists of the following main elements: energy source (a container or line with a gaseous or liquid energy carrier and oxidant); oscillatory system of a varying complexity (including the combustion chamber and control unit) with a definite dynamic characteristic; device controlling the energy input from the source into the oscillatory system in both the amount and the rate (the metered amount of energy defines the work accomplished by the GDG per a working cycle, while the rate, along with other system parameters, defines the frequency or cyclicity of GDG operation; the cycle energy and the GDG operation frequency will define its power). A feedback providing the control of the energy input (amount and rate) from the source into the oscillatory-system exists between this system and the control device. Because of a specific nature of the production processes accomplished, the GDG are also fitted with a source of the powder material processed (powder feeder), a device controlling the powder feed into the combustion chamber in the amount, rate, and time (the metered amount of powder will define the output and the useful work performed by the GDG per a working cycle; the feed rate and time interval, the spatial arrangement of powder in a fresh charge and the nature of its interaction with combustion products), a combustible mixture igniter, compressed gas sources for the powder feed and combustion chamber purging (cleaning); a feedback exists between the oscillatory system and the powder feed controller, the igniter (it provides for controlling the time between the combustion chamber filling and the combustible mixture ignition) and the purging gas controller, (provides for the control of the amount and rate of purging gas feed into the combustion chamber).

The conditions of processing powder materials are governed by the thermal, velocity, and chemical relaxation of particles in a high-temperature two-phase pulsed stream generated at every working cycle of the GDG. The relaxation of particles is conditioned by the parameters of the entire system under consideration and depends not only on the energy of a single pulse and the parameters of the high-temperature gaseous medium, but also on the spatial arrangement of a fresh gas charge and a single dose (metered amount) of powder.

The main elements of the working cycle of the GDG are: (1) barrel filling by fresh gaseous detonating mixture, (2) delivery of powder dose into barrel, (3) creation of phlegmatizer gas jam between the fresh mixture and the point of ignition, (4) ignition of fresh gaseous mixture, (5) flow off of barrel from remaining combustion products, (6) deflagration –to-detonation transition, (7) detonation products motion, (8) heating and acceleration of powder particles and outflow of two phase jet, and, (9) powder particles – substrate interaction and coating layer formation.

Elements 1-5 belong to the so-called preparatory ones, and elements 6-9, to independent ones which do not depend on the GDG control system. Functions of elements 1, 2, and 4 are clear from the essence of the GDG as an auto-oscillatory system, while element 3 is aimed at providing a localization of the burn-out of combustible mixture in the combustion chamber and preventing flashbacks into the GDG actuators and energy source. Independent elements 6-9 of the working cycle are separated for convenience of the analysis and organization of the control of processes proceeding at a pulsed burn-out of the combustible mixture.

It is possible to design GDG with different versions of combination of working cycle elements. The given traditional succession of elements is the *version 1* of working cycle. Varying the parameters of the preparatory elements of the working cycle and the design features of the GDG, predominantly of the combustion chamber, provides a means for controlling the independent (self-proceeding) elements of the working cycle and thereby, e.g., the coating formation processes.

A *version 2* represents a common combination in time of the processes of filling the combustion chamber with a fresh mixture and feeding the powder. We will now consider the specific features of other types of the GDG working cycle structure.

Version 3. When powder feed actuators are present, a command from the control system arrives after the delivery (or even execution) of the command for initiating the combustion. However, the time of operation of the pulse feeder of powder should be matched with the flame propagation time and with the period of its pre-detonation acceleration. In view of a considerable lag of powder feed devices, ignition and combustion chambers should be connected by passages providing for a delay of combustible mixture ignition in the barrel, sufficient for introducing the powder. Another way consists in using a direct combustion process for the powder feed.

Version 4. The powder feed is effected by the gaseous mixture combustion products in the detonation mode.

Version 5. Differs from the preceding one by the use of burnout products in the pre-detonation mode.

Version 6. Elimination of the combustion chamber "locking" is attained by means of special design features of the GDG, with the aid of hard-to-ignite combustible gases and at a relatively low frequency of GDG operation, which ensures cooling of the combustion products before filling of the combustion chamber.

Version 7. Differs from the preceding one in that the powder feed is carried out similarly to version 3.

Version 8. Differs from version 6 by a sequential filling of the combustion chamber with a fresh mixture and in the powder feed method.

Versions 9 and *10* are combinations of the specific features of structure 4 and 6, 5 and 6 respectively. Subsequent versions are derivatives from preceding ones and differ by a restriction of the combustible mixture burn-out by the pre-detonation mode: 11 corresponds to 1; 12, to 2; 13, to 3; 14, to 5; 15, to 6; 16, to 7; 17, to 8; and 18, to 10. Purging for removing residual gases is not considered since it is in fact combined with filling the combustion chamber with the combustible mixture.

The above-described features of the working cycle can be implemented in more numerous design versions of the GDG, but the working cycle of any of them consists of the above-considered elements. Their analysis will make it possible to create a scientific basis for calculating and designing the processes proceeding in the GDG. Comparing and evaluating different versions of the working cycle structure are possible only at a joint analysis of their design features and physical principles of GDG operation.

The sequence of accomplishing individual elements of the working cycle is given by the GDG operation cyclogram. The plants are of two types: with an adjustable (changes can be made, when required, in the cycle duration and operation of its individual elements as well as in the time intervals between them) and non-adjustable (rigid) cyclogram of the working cycle. The former type of cyclograms is typical for general-purpose GDG intended for depositing coatings of various types and on various products (having different service functions, shapes, sizes, arrangement of surfaces being coated). The latter type of cyclograms, which makes possible the use of simpler and more reliable control systems, is more preferable for special and specialized GDG.

The regularities of implementing the independent elements of the working cycle are primarily determined by the design features of ignition and combustion chambers, properties of the combustible mixture, and parameters of filling with a fresh combustible mixture and powder. Only a partial automation of the GDG control, associated with the execution of the working cycle, has been attained at present. The operator, however, has to interfere all the time with the GDG operation control at its starting (sequential feed of individual working gases and powder, switching-on of the ignition and actuation of protective devices to protect the surface to be sprayed until the plant reaches the working conditions, gaining of the working conditions by the plant, feed of the part being coated, monitoring the spraying process on instruments and visually) as well as with the spraying process when intolerable deviations from the parameters occur. The production process quality therefore depends to a great extent on the operator's skill.

D- GUN'S DESIGN CONCEPTS

In order to use propagating detonations for processing of powder materials and realize the D-guns advantages, a number of challenging fundamental and engineering problems has yet to be solved. These problems deal basically with low cost achievement and control of successive detonations in a gaseous detonation device. To ensure rapid development of a detonation wave within a short cycle time, one needs to apply (1) efficient fuel injection and oxidizer supply systems to provide fast and nearly homogeneous mixing of the components in DC; (2) efficient powder injection and supply systems to provide mixing of powder with gas mixture and controllable location into DC; (3) low energy source for detonation initiation to provide fast and reliable detonation onset; (4) cooling technique for rapid, preferably recuperative, heat removal from the walls of detonation chamber (DC) to ensure stable operation and avoid premature ignition of gaseous mixture leading to detonation failure; (5) geometry of the combustion chamber to promote detonation initiation and propagation at lowest possible pressure loss and to ensure high operation frequency and control of powder heating and acceleration; and (6) control methodology that allows for adaptive, active control of the operation process to ensure optimal performance at variable processing conditions, while maintaining margin of stability of repetitive two phase impulse jets. In addition to the fundamental issues dealing with the processes in the DC, there are other issues such as (7) efficient integration of DC with inlets and nozzles to provide high performance. The other problem is noise.

To date it are created manifold gaseous detonation guns (DG) which differ by mode of functioning (principle of operation) and embodiment. Therefore it is urgent question of estimation of technological capabilities, as advantages and shortages of different variants of DG and development of justified recommendations for their industrial application. For DG classification the next attributes are used: 1. types of fuel and oxidant; 2. typical mode of gas mixture burning; 3. type and design philosophy of barrel (configurations of transverse and longitudinal sections, micro geometry of barrel surface, type of cooling, attitude position); 4. type, location and operation mode of ignition generator; 5. technique of predetonation distance control; 6. peculiarities of gaseous exchange at barrel; 7. technique for gas mixture preparation and flow rate control; 8. initial gas mixture pressure at barrel; 9. technique for localization of gas mixture burning at barrel; 10. technique and point of powder injection into barrel; 11. ambient medium of spraying, and others.

Valved D-Gun concept implies the use of mechanical or electromagnetic valves to ensure a controlled (periodic) inward flow rate of fuel-oxidizer mixture into the DC, to prevent detonations or shocks from moving outwards from the DC through the inlet, and to provide a sufficient time for mixing of fuel with air. Several designs with mechanical or electromagnetic valves are available in literature. Fig. 3 shows the general view of compact D-Gun DNP8 with electromagnetic valves. These types of D-Guns are in industrial use.

Valveles D-Guns concepts imply continuous or intermittent supply of propellants (fuel and oxidizer) to the DC without using mechanical valves.

Predetonator concept implies the use of a two-step detonation initiation process in the DC, namely, the use of an additional, highly sensitive reactive mixture contained in a tube of small diameter and readily detonated by a source of low energy, and transmitting the obtained detonation wave into the larger-diameter DC containing considerably less sensitive reactive mixture. The small-diameter tube is referred to as predetonator.

Enhanced deflagration to detonation transition (DDT) concept implies the use of various passive means to promote DDT and obtain a detonation wave in the main DC with the working mixture ignited by a low-energy source.
Stratified-charge concept implies controlled injection of propellants into the D-Gun DC aimed at formation of the explosive charge with variable spatial sensitivity to detonation. Stratified explosive charge can be obtained by proper timing of fuel and/or oxidizer valves, by controlled distributed injection of fuel and/or oxidizer along the DC, or by various geometrical means creating a proper vertical structures in the barrel, or use of multipoint gas injection systems.

Multi-barrel schemes allow one to control the relative time of detonation products outflow, operation frequency, and productivity of gaseous detonation spraying. Most of the D-Guns schemes can be readily extended to multi-barrel configurations. In addition to the study of single-barrel D-Gun system performance, much effort was made to investigate the intricate combustion and gas dynamic processes in multi-barrel pulse detonation combustors.

CONCLUSION

The permanent efforts are directed to the achievement of the highest quality of coatings and productivity of GDS at lowest possible cost. This may be achieved:
Firstly: by better understanding of patterns of relationship of DGS operation cycle; by better understanding of gaseous detonation products interaction with processed powder; by search of methods for powder particles behavior control at impulse jet; by better understanding of impulse jet-substrate and particle-substrate interaction;
Secondly: by continuous improvement of process technology of DGS on basis of system approach and better understanding of materials interaction in process of coating

formation; by full control of all parameters involved in the GDS; by adequate GDS process simulation and optimization of all working conditions;
Thirdly: by development of the fully adaptive systems for GDS and the process monitoring devices.

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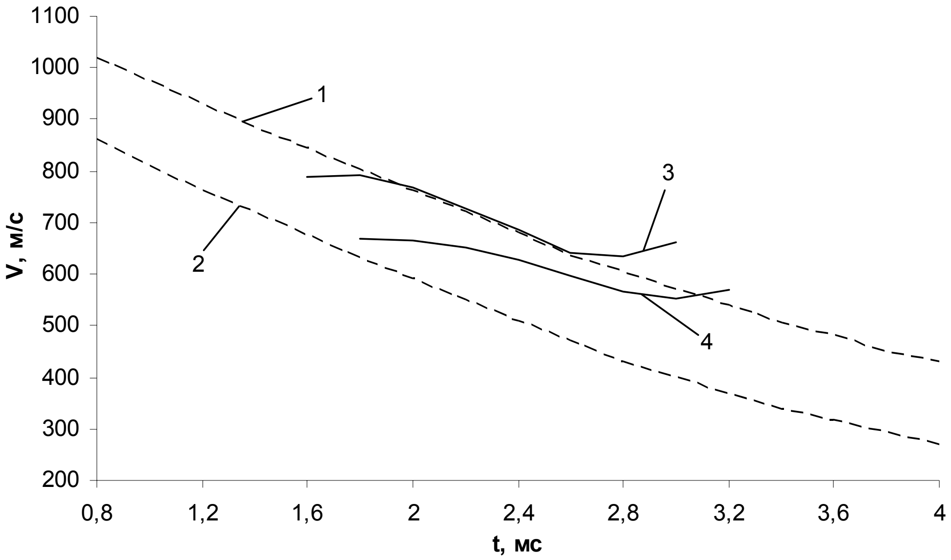

Fig. 1. Ni particles velocity dependence on outflow time. Process variables: distance spraying = 0.2 m; barrel length = 1.2 m and internal diameter = 20 mm; gaseous mixture C_3H_8+3,5O_2 (1, 3) and C_2H_2+O_2 (2, 4); powder doze = 0.15 g; initial distance between powder location and barrel exit = 0.6 m; particles diameter 20-40 μm (1, 2) and 30 μm (3, 4); experiment (1, 2); calculation (3, 4)

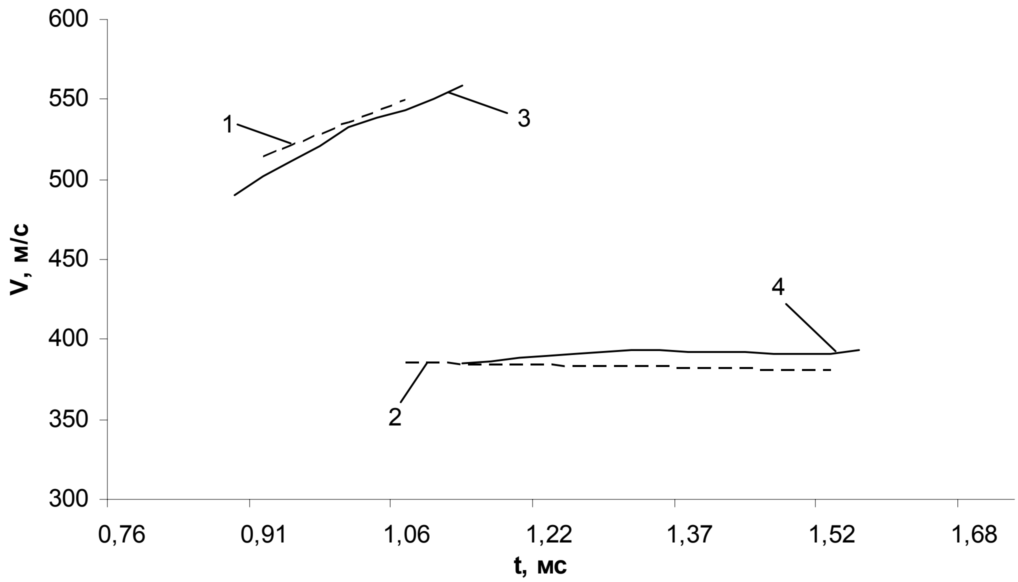

Fig.2. Alumina particles velocity dependence on outflow time. 1, 2 – mean experimental data [5]; 3, 4 – calculation. Process variables: barrel length = 0.95 m (1, 3 – tube with internal diameter 0.2 m and length = 0.75 m, and divergent nozzle with length = 0.2 m and angle of moving line = 2.9^o; 2, 4 – straight tube with internal diameter 0.2 m); gas mixture C_2H_2+2,5O_2; particle diameter 87 μm; spraying distance 35 mm; initial distance between powder location and barrel exit = 0.3 m

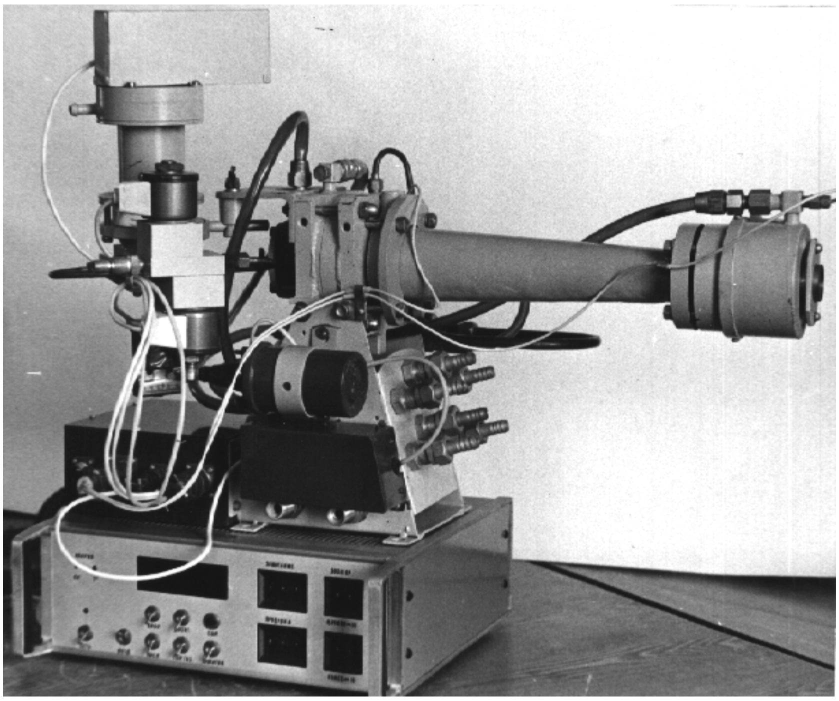

Fig.3. General view of the detonation gun DNP8