2005 WJTA American Waterjet Conference
August 21-23, 2005 • Houston, Texas

Paper 3A-1

APPLICATION OF NUMERICAL TECHNIQUES FOR OPTIMIZATION OF THE WATER CANNON DESIGN

O.P. Petrenko, T. G. Bitadze, E.S. Geskin
New Jersey Institute of Technology
Newark, New Jersey, U.S.A.

O. Rusanova, A.N. Semko
Donetsk National University,
Donetsk, Ukraine

ABSTRACT

The performed studies demonstrated feasibility of the use of the high speed impulsive jets for a wide range of technological operations, such as the structure demolition, explosive neutralization, material processing, etc. All of these applications require integration of the jet launcher (water cannon) into a robotic cell. Such integration limits the acceptable weight and size of the water cannon. Due to complexity of the experimental procedure the only realistic approach to the system optimization is numerical analysis based on the proven process models. A numerical technique based on the solving of the material and momentum conservation equations was used for analysis of the water acceleration. This technique, developed earlier by G.A. Atanov, was demonstrated in a number of experiments. Various numerical procedures of the water cannon optimization were explored and the avenue of the device improvement was identified. Particularly the feasibility of the dramatic improvement of the cannon operation via optimization of the barrel geometry was demonstrated.

Organized and Sponsored by the WaterJet Technology Association

1 INTRODUCTION

The objective of this work is to evaluate quasi-optimal values of the operational and design parameters of a launcher (water cannon) for generation of high speed water projectile (impulsive jets). The water cannon constitutes a device where energy is injected in a liquid (water load) placed in a barrel with an attached nozzle. In a way, the water cannon is a rifle where a solid slug is removed from the round and replaced by a liquid load and where a converging nozzle is attached to the barrel. This modification enables us to increase the speed of the generated projectile in two-three times and perhaps much more. The actual potential of the water cannon is yet to be determined.

Comparatively to a bullet fired by a rifle the additional acceleration of the water projectile is due to the flow converging in the nozzle and superposition of the compression and rarefaction waves in the fluid. However the main contribution to the generation of high velocity projectiles is due to the energy redistribution in the course of the unsteady flow in the barrel and nozzle. As the result of this redistribution the front of the water load accelerates to a high velocity. It is obvious that the complicated chain of energy transfer processes (from an energy source to the liquid load and then within the liquid projectile) is highly parameter sensitive. At the same time existing water cannons were designed on the base of the feasibility consideration only. A number of the performed experiments, both industrial and laboratory, evidently demonstrates process feasibility [1]. Numerical model describing velocity and pressure within the cannon was also developed and validated [2]. It is necessary now to utilize the acquired knowledge for evaluation both cannon design and operation. Such evaluation will enable us to improve this device as well as to develop a techniques for development other jet based devices and processes.

Two different optimization problems were posed. The first one involved selection of the interior geometry of the cannon as well as the specific energy supply which maximizes the effective (available) momentum of the projectile. In this problem the objective function is the effective momentum of the projectile while the specific energy and cannon interior geometry are independent variables. Two numerical techniques were used to evaluate the sought variables. The first one involved a numerical evaluation of various combinations of the control variables and comparison of the obtained value of the objective function. The factorial analysis was used in this study. Another technique was based on the commercial optimization package provided by the MATLAB.

The second problem involves reduction of the cannon weight at a given pressure distribution along the cannon. Commercial packages used for determination of the stress distribution in axysymmetric enclosures at a given pressure distribution along the cannon axis and the cannon geometry. Then, the yield criterion was evaluated for 3 different geometries. The comparison between actual maximal value of this criterion and its critical value were used to evaluate the cannon design. The performed computations enabled us to suggest improvements of the water cannon design and operation.

2 EVALUATION OF THE CANNON GEOMETRY

2.1 Problem Overview.

The water cannon design is illustrated by the schematics Figs 1 and 2. In this device powder combustion is used as an energy source. A computational procedure for prediction of the pressure and velocity distribution along the water cannon, developed earlier [2], constitutes a base for evaluation of the device efficiency.

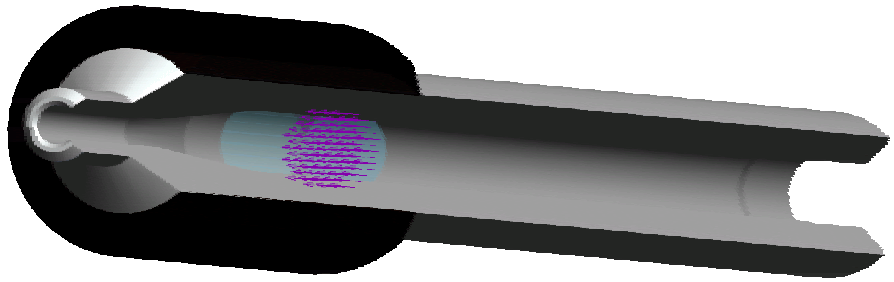

Fig. 1 General schematic of the cannon

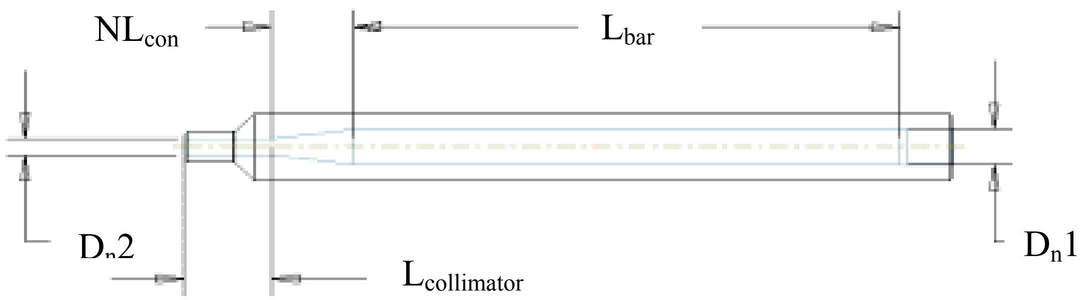

Fig. 2 Detailed view if the barrel

This procedure enables us to determine the time variation of the space distribution of the water velocity and pressure. The examples of the application of this procedure are depicted on Fig. 3 which shows velocity distribution during the process. The results are obtained for the different length of the barrel. The objective of the cannon operation is formation of the projectiles which bring about deformation of ductile and breakage of the brittle materials. The effect of an impacting particle on a target is determined by the dimensionless damage number

$$D=\rho V^2/\sigma \tag{1}$$

If the actual damage number is less than the critical one, the impact does not affect the target. Total effect of the projectile can be evaluated by the momentum of the water having the velocity, which assures the magnitude of the damage number exceeding the critical level. It is clear that the rest of the impacting water will not affect the target. Because the maximum of the water velocity is attained at the beginning of the process and the velocity function is monotonous, the water momentum which affects the target (the effective water momentum) is given by the

$$M_{effective} = \int_{t}^{t_{cutoff}} \rho F \upsilon^2 dt \tag{2}$$

equation. Here t_{cutoff} determines the time when the velocity of the jet drops below the critical level. As it follows from (Fig.3) the monotonous change of the water exit velocity enables us to relate the water velocity to the time.

The integral (2) can be used for evaluation of the effective momentum. In order to achieve this it is necessary to determine the t_{cutoff}. In principle this time is determined by the process duration when the water velocity reaches the critical level determined by the minimal value of the damage number. However, because the value of D for a given target usually is unknown, it is convenient instead to determine t_{cutoff} by the time when the exit velocity constitutes a selected fraction of the maximal water velocity. From the practical consideration, in our analysis the cutoff velocity constitutes 85% of the maximal one.

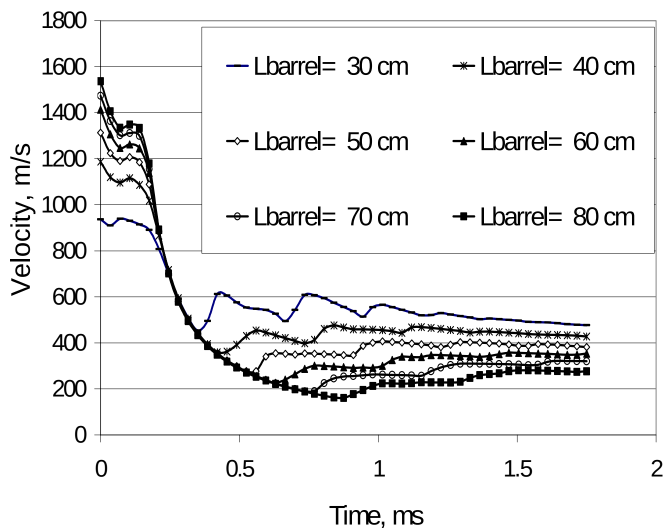

Fig. 3 Outflow velocity vs. time at diff. barrel length

Now the search of the operational and design variable can be reduced to the selection the values of the variables which maximize the integral (2) while the process constraints are determined by the system of equations relating fields of the water pressure and velocity. The direct search of the quasi-optimal values of the process variable (Factorial Analysis) is used for solving a problem in question. Large number of process variable and complicated process model made it difficult if not impossible to use more sophisticated optimization techniques.

Variation of the water velocity and pressure along the cannon axis in the course of the projectile formation is depicted on Figures 4 and 5.These figures show respectively velocity and pressure in x-t space, where x represents the length of the nozzle, t - the moment of inflow.

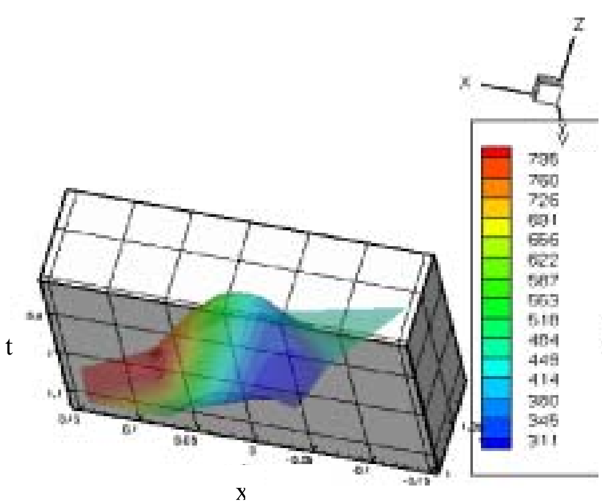

Fig. 4 Water velocity distribution plot with 100g water load

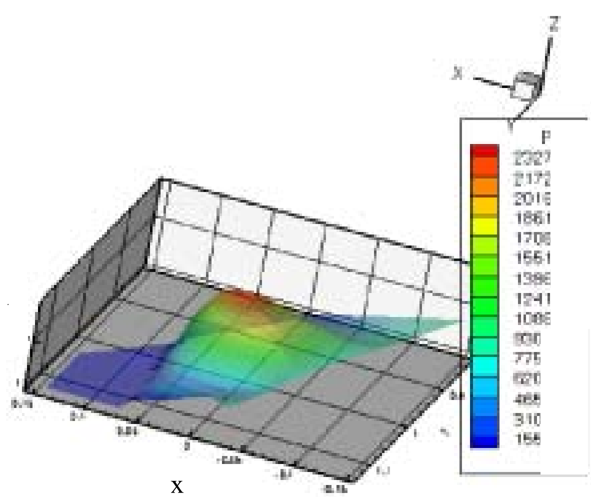

Fig. 5 Pressure distribution plot with 100g water load

The objective of the performed search was to determine the profile of the water cannon and the specific energy of the process. The specific energy is determined by the ratio between the water and powder mass, while the geometry of the cannon interior is characterized by the length of the conic part of the nozzle, nozzle inlet diameter, nozzle outlet diameter, collimator length and barrel length. A preliminary qualitative analysis and quantitative estimation were used to determine the range of the process variables. Then the selected process variables were digitized and various combinations of these variables were selected randomly (Table 1).

Table 1 Sets of varied variables

Set 1				**Set 2**				**Set 3**		
L_{bar}	D_n2	D_n1		L_{bar}	D_n2	D_n1		L_{bar}	D_n2	D_n1
280_e-3	5_e-3	30_e-3		290_e-3	19_e-3	31_e-3		270_e-3	21_e-3	29.5_e-3
380_e-3	15_e-3	32_e-3		300_e-3	18_e-3	32_e-3		260_e-3	22_e-3	29_e-3
700_e-3	20_e-3	64_e-3		310_e-3	17_e-3	33_e-3		250_e-3	23_e-3	28.5_e-3

The shaded cells of the Set 1 represent actual parameters of the existing water cannon prototype. The other two sets of each parameter were selected in order to explore the available domain of process variables. The computations involved The integral (2) was used for the determination of the effective projectile momentum at the selected process variables. Totally 27 possible combinations of varied parameters were explored. .Analysis of the various modes of the process output at non monotonous function behavior was examined. Breaking down changes of geometric parameters enables us to understand and explain crucial factors influencing on momentum. Quantitative analysis enables us to evaluate factors that determine the formation of the most "powerful" water slug. Tracking tendency of changes occurring throughout the barrel and nozzle determines a set of boundaries providing the upper limit of the functions affecting the process. It should be noted that the best of the observed results has been obtained at the existing operational and design condition, which have been found in the course of the experimental trial and error research. A peculiar momentum change is depicted on Fig.6. Here the extremum is reached at short NL at the lowest water load. For the illustration the graph with the minimal value of the integral (Eq.2) in the same domain of Set 1 is presented on. Fig. 7.

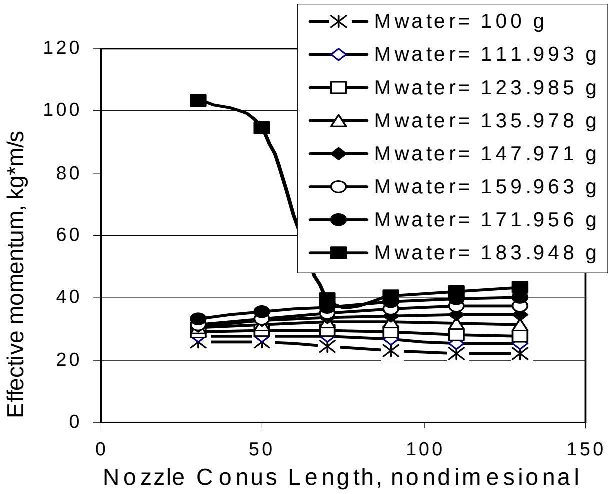

Fig. 6 Impulse Integral vs. Water Load

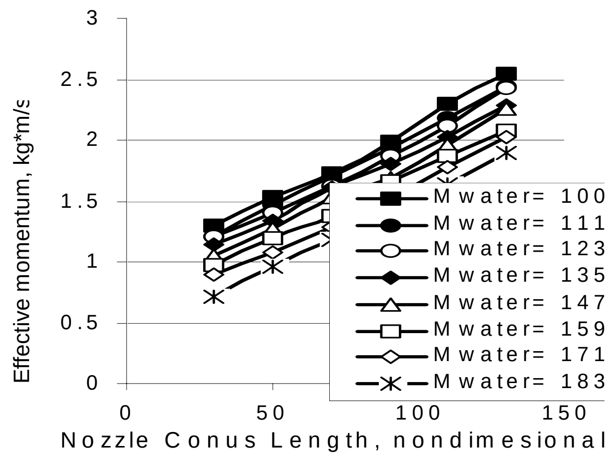

Fig. 7 Impulse Integral vs. Water Load

The effect of the cutoff factor on the cannon performance is illustrated by Figs 8 and 9. Figure 8 shows two cases (not optimal) of the exit velocity variation determined by the nozzle length. The variation of the effective jet momentum in the processes depicted on Figure 8 is shown on Fig. 9. As it follows from these two figures, practically insignificant velocity difference (7%) brings about dramatic difference in the process effectiveness (almost 100%). This result is due to the velocity cutoff, which determines the duration of the interval when the effective jet is generated. Due to cutoff velocity a small difference in the flow velocity results in significant difference in the duration of the formation of the effective water stream. In fact, such difference in the estimation of the process effectiveness reflects its actual performance. If the impulse of the projectile less than critical one, regardless of the magnitude of this difference the projectile does not affect the target. The Figures 8 and 9 evidently demonstrate the strong effect of the operational and design conditions of the process results.

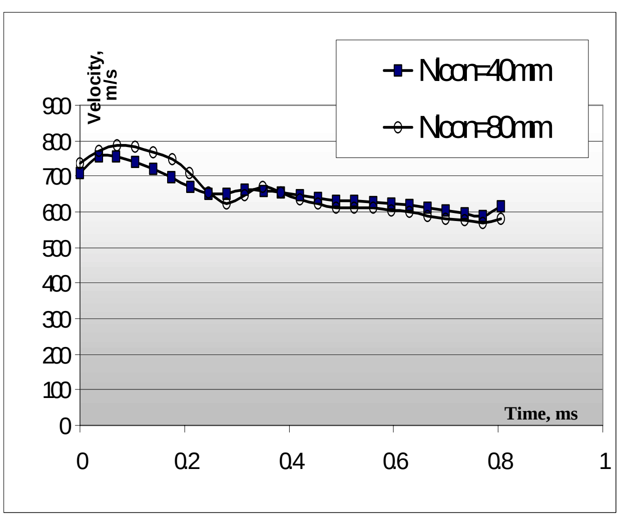

Fig. 8 Outflow velocity

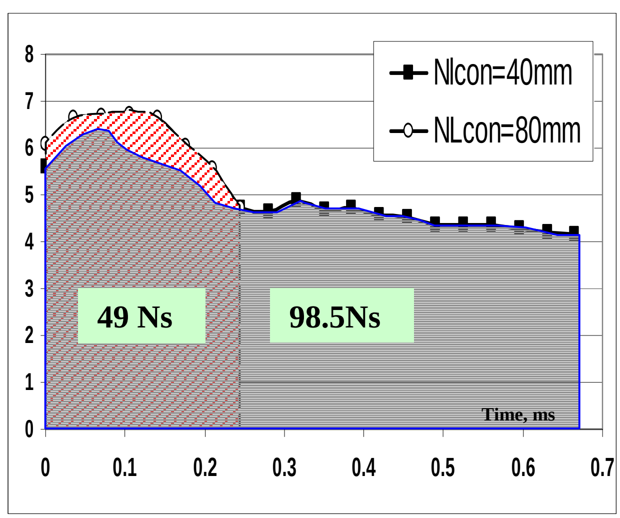

Fig. 9 Momentum integral at cutoff = o.8

4 NOZZLE GEOMETRY OPTIMIZATION

Another approach to numerical analysis of the water cannon operation involves the use of commercial package provided by Matlab optimization toolbox algorithms were incorporated into the program simulating water cannon operation. The implemented procedures search for unconditional local maximum in the unbounded multivariable space and was used for optimization of the nozzle shape. The nozzle geometry was approximated by two intersecting cones.

The length of the nozzle and its inlet and outlet diameters were constant and equal to

$$L_{nzl}=0.07m,\ R_{inlet}=0.016m,\ R_{outlet}=r_{col}=0.0075m \tag{3}$$

Thus a region in two-dimensional space was formed, where x represented the length of the first cone, and y –the radius of the cones intersection. This region in x-y space was determined by the constraints of the position of the cones connection. It should be more than zero and less than the total length of the nozzle. The constraints were also imposed on the radius of the intersection that should vary between radii of inlet and outlet cross sections. Finally, the convergence angles should be not exceeding 45º.

Thus

$$x=L_{con1}\in [0,\ 0.07] \tag{4}$$

$$y=R_{con1}\in [0.0075,\ 0.016] \tag{5}$$

$$x+y-0.016\geq 0 \tag{6}$$

$$x+y-0.0075-0.07\leq 0 \tag{7}$$

The barrel length was adjusted so that the internal volume of the cannon was constant at variable nozzle shape. This constrain is necessary to control the work of the combustion products which depend on the available volume.

The integral of the effective projectile momentum was used as the optimization criterion:

$$I=\pi r_{col}^{2}\int_{0}^{t_{stop}}\rho_{o}v^{2}dt \tag{8}$$

where t_{stop} is defined by condition $v \geq 0.85\ v_{max}$, i.e. only the relatively fast fraction of the slug was taken into account, because only this part determines the obstacles destruction. The function calculating the criteria was set to zero when the arguments were out of the allowed region.
The results of the optimization are presented on the Figure 10

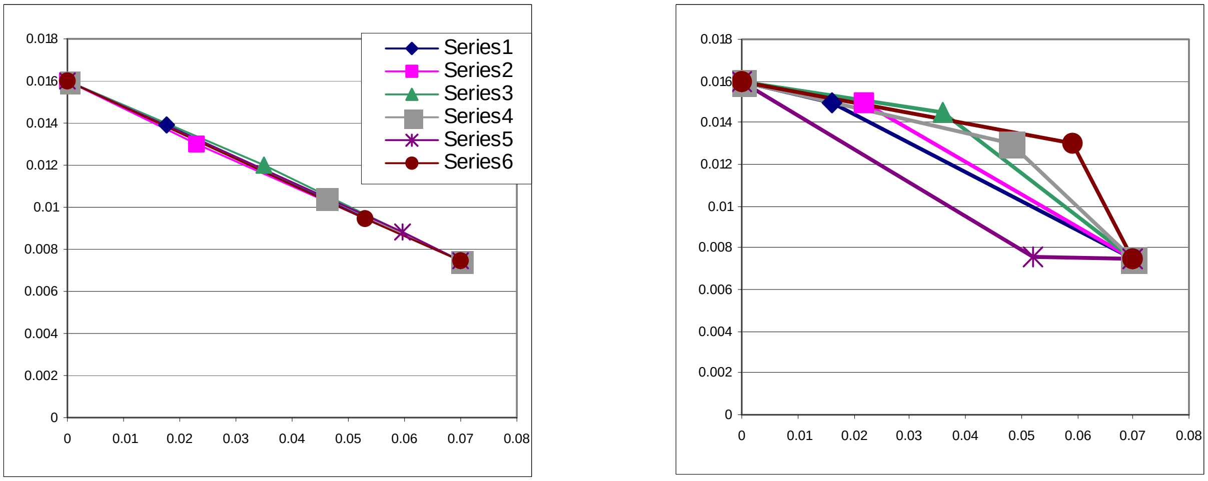

Fig. 10 Initial a) and optimized b) nozzle profiles

A consecutive search was run afterwards to check the optimization results and visualize the objective function for design of a new nozzle. (Fig. 11) As it is shown on Figure 11 the maximum of the selected criterion is located in the region of the maximal convex curvature and the maximal length of the first cone. Objective function varies 16% on the selected region, while the maximal velocity shows only 3% variation. This suggests that the slug has a very different rate of decrease of the outflow velocity at different nozzle configurations. Thus, the concave nozzle has a lower slug quality due to faster decrease of the outflow velocity and subsequently its faster disintegration. The chart of the integral of the effective kinetic energy has similar shape because only the mass multiplier significantly varies and the velocity multiplier is about the same.
The developed optimization algorithm can be used for estimation of the various water cannon parameters. However in the course of the search of the global extremum several starting points should be used.

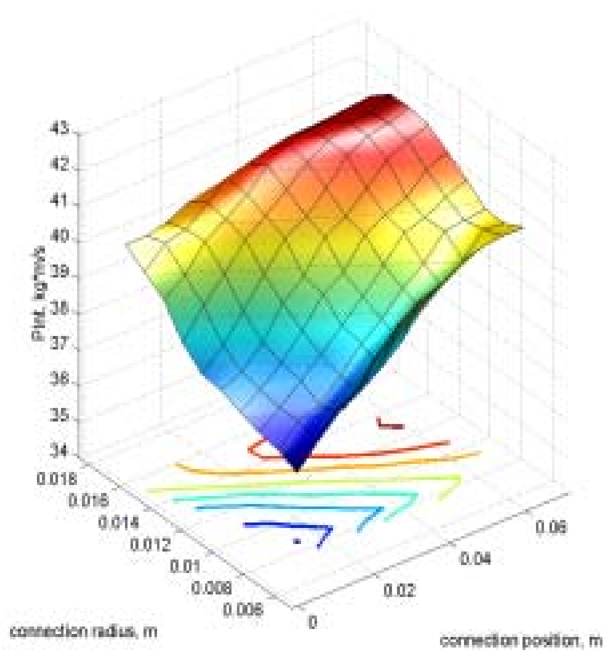

Figure 11 Effective momentum integral of a slug at different nozzle configurations.

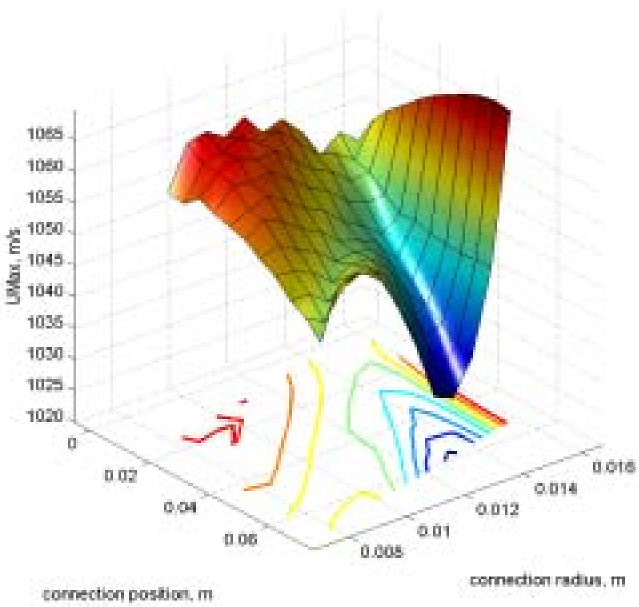

Figure 12 Maximum outflow velocity of a slug at different nozzle configurations.

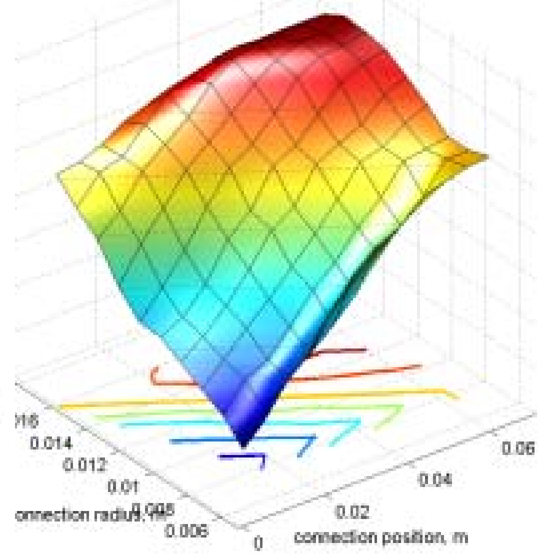

Figure 13 Effective kinetic energy integral of a slug at different nozzle configurations.

5 WEIGHT MINIMIZATION

The previous study we were concerned with improvement of the water flow through the water cannon. Another optimization problem is reduction of the cannon weight. The device will be guided by a robotic arm, thus its weight must be minimal. The cannon should withstand the maximal stresses developed in the course of the projectile formation that is the maximal stresses over the entire cannon volume do not exceed critical stresses, determine by the von Mises criterion. The cannon design should minimize the thickness of the cannon wall, which assure permissible level of the maximal stresses. The ANSYS package was used to determine the stresses in the cannon wall. These stresses were found at several possible cannon designs. As it is shown on Fig. 14 the design optimization enables us to reduce the cannon weight by 20-30%. Further reduction, perhaps by 50% can be achieved by the use of composite materials. It is expected that weight of powder fed device will be in the range of 10-20 kg.

Solving the problem involves ANSYS/Structural Analysis utilization which allows carrying out a stress analysis of system with various physical and geometrical nonlinearities. The problem was solved in domain of theory of elasticity with the consideration of contact deformations. Due to the symmetry the axysymmetric model was used for the solution. Finite Element Model consists of 19,000 nodes; the size of the element is 10e-3 m^2. A discretization is performed with the solid 8-node element PLANE 82 which permits to solve the axysymmetric problems and build a quite fine mesh. The computations was carried out at the following steel properties: Young's modulus E = 2e+11 Pa, Poisson's ratio ν=0.3, friction coefficient between the barrel and the rim μ=0.2 Internal pressure calculated by Godunov method [4] is set up by mesh function in 128 dotes not connected to the nodes of the mesh using *SET,PAR function which defines data needed to be read from the output file to the database. ANSYS uses linear interpolation for the load definition in nodes of mesh.

According to the fourth energy method in strength theory:

$$\sigma_{eq} = \sqrt{1/2((\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_2))} \le [\sigma] \tag{9}$$

Here σ_{eq} - von Mises stress; $\sigma_1, \sigma_2, \sigma_3$ - principal stresses;

For the material of the actual device $[\sigma]$ = 1520 Mpa, von Mises stresses distribution plot is shown in the Figure 14. It can be concluded that the weight of the device might be decreased.

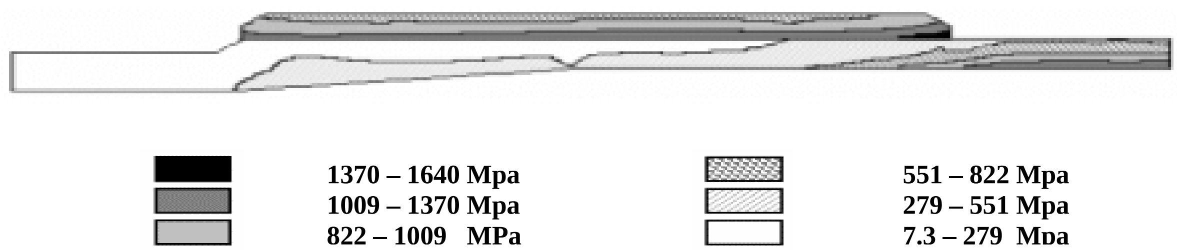

Fig. 14

From the Figure 15 a) follows that a hydro cannon has the excessive yield strength. For the industrial manufacturing that kind of level of the strength is not acceptable. With the decreasing of external diameters of the barrel and the rim by 20% the distribution plot of the von Mises criterion is depicted on Figure 15 b). The external radius of this device equals to 0.315 m; the radius of conjunction of two parts equals to 0.235 m, and as a result interference is 176e-06 m. In the Figure 15 b) it is shown that the device is safe and the weight is reduced by about 20%. Figure 15 c) illustrates equivalent stress distribution plot when barrel was exposed to the maximum pressure with no rim on it. Since the maximum stresses in the Figure 15 c) exceed critical ones the necessity of the clutch had been justified.

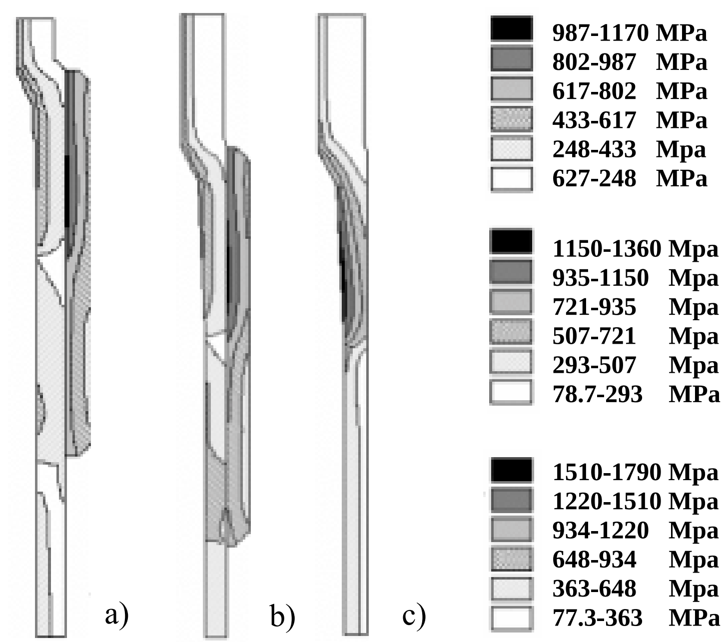

Fig. 15

CONCLUSION

Numerical modeling of slug formation provides the necessary preprocessing data for analysis, design and further study of the water cannon. It is indicated that the nozzle geometry has significant effect on the device operation and must be determined from the conditions of the process optimization. Most probably, the cannon might have curvilinear axial cross section. At the same time water cannon might be not necessarily a solid body but might consist of separate parts. Various kinds of nozzles could be attached to the barrel depending on industrial or military task being executed. Eventually, the optimization of the available data will bring about substantial process improvement. The presented procedures can be utilized for improvement of other jet technologies. The major concern in the application of the optimization technique is lack of information. However the optimal value belongs to the extremum of the objective function, where the effect of the process variables on the objective function is rather weak or to the limit values of the process variables where the result is fixed. Thus, even processing of low quality information enables us to receive the important guidance to the process improvement.

NOMENCLATURE

NL_{con}	length of the conic part of the nozzle
M_o	water load mass
L_{bar}	barrel length
D_n2	nozzle outlet diameter
D_n1	nozzle inlet diameter
r_{col}	collimator radius
t_{sto}	time of integration (3.1) stop
ρ_o	water density at normal conditions
v	outflow velocity
v_{max}	maximum outflow velocity attained during a shot
L_{nzl}	length of the nozzle
R_{inlet}	inlet radius of the nozzle
R_{outlet}	outlet radius of the nozzle
R_{con1}	radius of the connection between two cones constituting the nozzle
L_{con1}	length of the first of the two cones constituting the nozzle
y	optimization variable, $y=R_{con1}$
x	optimization variable, $x=L_{con1}$
D	dimensionless number
V	water velocity
σ	yield stress
$\sigma_1, \sigma_2, \sigma_3$	principal stresses
σ_{eq}	von Mises stress
ρ	water density

ACKNOWLEDGEMENT

This work was supported by the NSF award DMI-9900247

REFERENCES

[1] Atanov, G.A. (1977) Internal Ballistics of Hydro Cannon and Impulsive Water Extruder, Donetsk State University (Russian), Donetsk, USSR

[2] Godunov, S.K. et al. *Numerical Solving Multidimensional Problems of Gas Dynamics,* Nauka, Moscow, USSR

[3] Petrenko O., Geskin E. S., Atanov G. A., Semko A., Goldenberg B. (2004) *Numerical Modeling of Formation of High-Speed Water Slugs,* NJIT, USA