9th INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2020
Belgrade, Serbia, 8 – 9 October 2020

ANALYSIS OF THE INFLUENCE PARAMETERS ON THE PRESSURE FIELD IN THE HYDRAULIC BRAKE

DEJAN JEVTIĆ
University of Belgrade, Faculty of Mechanical Engineering, djevtic@mas.bg.ac.rs

DEJAN MICKOVIĆ
University of Belgrade, Faculty of Mechanical Engineering, dmickovic@mas.bg.ac.rs

PREDRAG ELEK
University of Belgrade, Faculty of Mechanical Engineering, pelek@mas.bg.ac.rs

MILOŠ MARKOVIĆ
University of Belgrade, Faculty of Mechanical Engineering, mdmarkovic@mas.bg.ac.rs

LANA JARAMAZ
University of Belgrade, Innovation Center, Faculty of Mechanical Engineering, ljaramaz@mas.bg.ac.rs

---

Abstract: *The pressure change in time in the hydraulic brake of the automatic cannon depends on many factors such as the geometry of the brake, the velocity of the piston, the amount of the hydraulic oil in the brake, elevation angle of the cannon, etc. The analysis was made at the extreme values of the temperature interval of the cannon usage as well as the normal temperature since the temperature affects the properties of the hydraulic oil. The numerical simulation of the flow field in the hydraulic brake during recoil was performed in CFD software ANSYS Fluent. The simulation was made in a 2D numerical domain based on the flow geometry in 3D space. Due to the flow field boundaries movement during the process, the dynamic mesh was employed. The dynamics of the hydraulic brake piston was determined using the solver in which the forces that act on the gun are defined by the User Defined Function file. The experiment was performed by firing from the 20mm M55 gun mounted on the stand. Experimental results contain pressure change in time inside the brake which was measured by the piezoelectric pressure sensor. The dynamic behavior of the cannon was recorded by the high-speed camera. The numerical results of the pressure change and position of the gun deviate within acceptable limits with respect to experimental results. Based on that, further analysis of the influence parameters on the hydraulic brake force can be done by numerical simulation.*

Keywords: *automatic cannon, hydraulic brake, pressure field, numerical simulation, experimental results*

1. INTRODUCTION

The hydraulic brake that is mounted on the 20 mm M55 anti-aircraft gun has the purpose to absorb the energy of the gun in the final stage of recoil and the counter-recoil. The brake doesn’t provide great resistance while the breech block is still locked to the gun barrel. The reason for this is to allow the higher velocity value of the gun at the moment of the breech block unlocking. There are two ways to control the hydraulic resistance of the brake: by the flow surface area at the gun path during the selected period and by the amount of the hydraulic oil inside the brake. After the breech block unlocking, it is necessary to stop the gun as soon as possible because the rate of fire is strongly influenced by the relative velocity between the breech block and the gun. To analyze thermodynamic phenomena that occur in the hydraulic brake during the recoil of the gun, numerical simulation was performed in the CFD software ANSYS Fluent. The simulation was done in the 2D numerical domain. Since the whole flow process inside the brake depends on the velocity of the piston, the dynamic mesh was employed. The velocity change in time was determined by the forces that act on the gun and they are taken into account by the Six Degree of Freedom (SDOF) solver using the User Defined Function (UDF) file. A similar approach was used in [1] and [2], where different types of hydraulic brake were analyzed. Authors of the paper [3] presented the numerical simulation of the flow field parameters in the brake using the dynamic mesh without taking into account the heat transfer between the oil and the metal parts of the brake. Verification of the numerical results in this paper was done using the experimental results which contain of pressure change in time inside the brake measured by a piezoelectric sensor. Also, shots from the high-speed camera provided the movement of the gun during recoil. Based on the good agreement between experimental and numerical results, it was concluded that numerical simulation can provide the change of the flow field parameters that are difficult to measure experimentally. Besides the influence of the flow field geometry and the hydraulic oil amount on the hydraulic brake force, in this paper was analyzed how the gun elevation angle and the oil initial temperatures affect the pressure distributions and their change in time. Only the recoil process was taken into consideration. Due to the symmetry of the brake with respect to the plane that is normal on the brake axis, similar phenomena will occur during recoil and counter-recoil process.

2. WORKING PRINCIPLE

The recoil mechanism of the 20mm M55 automatic gun is shown in figure 1. The recoil mechanism is located on the rear side of the gun, along the gun barrel axis. As can be seen in the figure, the cylinder with the bushing of the hydraulic brake is stationary during the firing cycle and the piston with the piston rod is moving. Along with the cannon recoil, the return piston deforms. Since the hydraulic brake is not completely filled with the oil before the firing, in the brake is the air at the atmospheric pressure. During the gun recoil, the piston rod is entering into the cylinder which causes small air pressure to rise. At the same time, the oil level in front of the piston forehead is rising. The velocity of the oil level rising depends on the piston velocity. Until there is only the oil in front of the piston forehead, hydraulic resistance in the brake can be neglected. As the piston further move, the flow surface from working to non-working volume decreases. When the piston forehead reaches the end of the bushing grooves, the flow surface is the gap between the piston and the bushing. In some cases, depending on the piston velocity, intensive pressure jump can be produced in this moment. This will cause a sudden piston velocity drop. This prevents the damage that can occur due to the prolonged recoil length. The side surface of the piston is rounded, so the flow area gradually decreases with the piston movement.

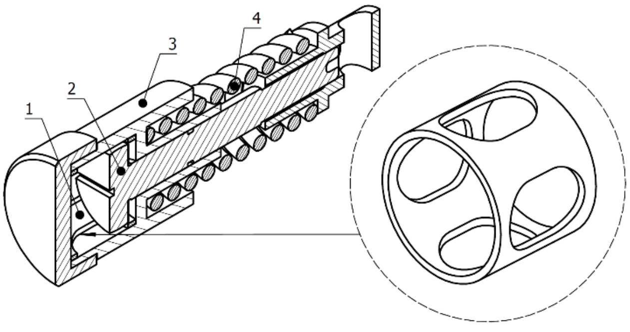

Figure 1. Recoil mechanism of the 20 mm automatic cannon: 1-bushing of the hydraulic brake; 2-piston and piston rod; 3- cylinder; 4-return spring;

3. NUMERICAL SIMULATION

To investigate the influence of some factors on the pressure change in time in the hydraulic brake during the recoil process of the gun, numerical simulation in the ANSYS Fluent software was performed. The simulation was performed in 2D geometry, which was obtained based on the 3D geometry of the hydraulic brake. During the conversion of the flow domain, it is necessary to maintain the ratio of the piston forehead surface and the cross-section area of the grooves at the position of the piston forehead. The piston forehead area is chosen as the reference area and based on that the third dimension in 2D numerical domain was determined. All other dimensions that describe the flow field in the hydraulic brake were determined from that dimension. Since there are four grooves on the hydraulic brake bushing, it was adopted that two grooves in 3D geometry are merged in one in the 2D numerical domain. In the real hydraulic brake, the opposite side of the piston forehead is in the contact with the cylinder bottom. For the purpose of the dynamic mesh creating on that side of the piston, it was necessary to create the gap between the piston and the cylinder. The numerical domain for the simulation is shown in Figure 2. as the reference elevation angle of 45° was chosen. In order to decrease the cells number in the numerical domain, only the layer of certain thickness of the metal parts (cylinder, piston, and piston rod) was taken into account. This is justified since, during the gun recoil, the thermal wave depth in these parts is very small. The generated grid was unstructured with inflation layers around the metal parts to improve the flow in the boundary layer and the heat transfer.

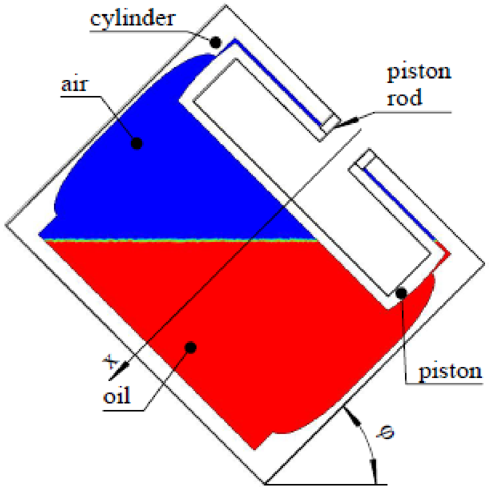

Figure 2. Numerical domain for numerical simulation of pressure field in the hydraulic brake

The motion law of the piston (translational motion of its center of mass) is defined by the UDF file [4] which is compiled in SDOF solver for dynamic mesh purpose. The differential equation of motion while the projectile is in the barrel is:

$$m_g \ddot{x} = F_{pb} - F_r + m_g g(\sin\varphi - f\cos\varphi) - F_p - F_{hb} \quad (1)$$

where m_g denote the gun mass; x- the coordinate along the gun barrel axis; F_{pb}-pressure force of the powder gases that acts on the breech block; F_r-return spring force; φ-elevation angle; f-friction coefficient; F_p-interaction force between the gun barrel and the projectile; F_{hb}-hydraulic brake force.

When the projectile leaves the barrel (after about 3.8 ms), muzzle brake starts to act. The motion of the piston in this period is described with the next equation:

$$m_g \ddot{x} = F_{pb} - F_{rs} + m_g g(\sin\varphi - f\cos\varphi) - F_{mb} - F_{hb} \quad (2)$$

where F_{mb} denote the muzzle brake force;

When the breech block of the gun is unlocked (after about10.3 ms), differential equation of the gun motion is:

$$m_g \ddot{x} = F_{rs} + m_g g(\sin\varphi - f\cos\varphi) + \\ + m_{bb} g \cdot f \cos\varphi - F_{hb} \tag{3}$$

where F_{rs} denote return spring force; m_{bb}-breech block mass;

During the cartridge case extraction, it was assumed that there is no friction force between the cartridge case and the barrel. When the breech block is open, there are intensive gun powder gases leaking on the rear barrel side. Due to that, there is a sudden drop of the muzzle brake force, so that it can be neglected from the beginning of the last period of the gun recoil. The return spring force that acts on the gun can be neglected. The change in time of the force that acts on the gun during the interior ballistic cycle is shown in figure 3. The gas pressure force on the breech block (red curve in Figure 3.) was obtained from interior ballistic calculations [5]. The force of the muzzle brake (black curve in Figure 3.) was obtained by the numerical simulation in ANSYS Fluent.

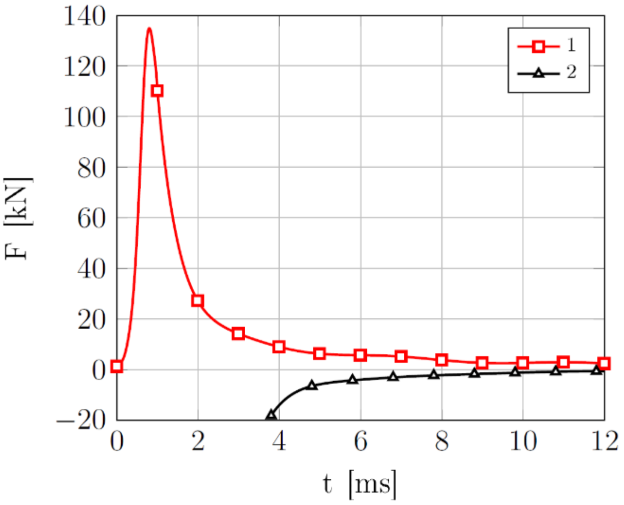

Figure 3. Forces that act on the gun: 1-gas pressure force that on the bolt; 2-muzzle brake force

The mixing process of the air and oil during the gun recoil was taken into account by the multiphase model (Volume of Fluid). The turbulent flow was modeled using the RNG $k-\varepsilon$ model with scalable wall functions. The viscous heating was taken into account. The numerical scheme that was used in the simulation is PISO. More about this scheme can be found in [6]. The spatial discretization of the pressure field in the brake was done using the PRESTO! scheme. The density, momentum and energy were discretized by the Second Order Upwind scheme.

4. VERIFICATION OF THE NUMERICAL RESULTS

Verification of the results obtained by the numerical simulation was done using the experimental results. The experiment was performed on the proving ground by firing 20 mm M55 gun positioned on the stand at the elevation angle $\varphi = 0°$, which can be seen in Figure 4. Experimental results contain pressure distribution in time in the hydraulic brake which was measured by the piezoelectric pressure sensor KISTLER 601C. The diagrams shown in figure 5. represent the pressure distribution in time inside the hydraulic brake during recoil of the gun, obtained by experimental measurements and by numerical simulation. From the beginning of gun recoil to approximately 9 ms, the pressure slightly changes from its initial value (see figure 5). During this period of the piston movement through the cylinder of the hydraulic brake, the pressure change at the sensor position is caused by the air compression caused by the piston rod entering into the cylinder.

Figure 4. Anti-aircraft gun 20 mm M55 on the stand

At the same time, the rise of the oil free surface occurs. When the oil reaches the upper groove of the bushing, hydraulic resistance on the piston movement occurs, which causes the pressure increase in the brake. Pressure change in the working volume during hydraulic resistance is directly proportional to the square of the piston velocity and inversely proportional to the square of the flow surface of the grooves [7]. After the maximum pressure is reached, the piston velocity decreases faster than the flow surface area which results in the fast pressure drop in the hydraulic brake.

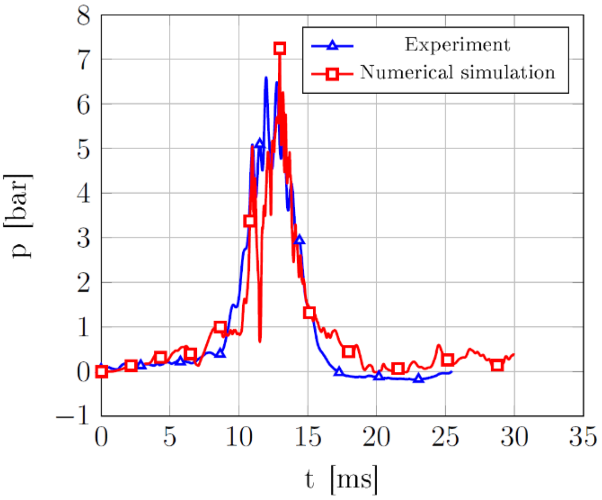

Figure 5. Experimental and numerical results of the pressure change in time in the hydraulic brake

In order to analyze the dynamics of the gun, recoil and counter-recoil processes were recorded by the high-speed camera. Results of the gun position change in time during the recoil can be seen in figure 6. In the figure are presented results obtained from high-speed camera shots as well as the recoil length obtained from the numerical simulation. The high-speed camera was set up at 1000 fps. Maximum recoil length obtained by numerical simulation is approximately 25 mm, and the time when the recoil is finished is 17.5 ms. On the other hand, the experiment shows that the maximum recoil length is 26 mm and the recoil time is 19 ms. The numerical results deviate from experimentally obtained results within acceptable limits.

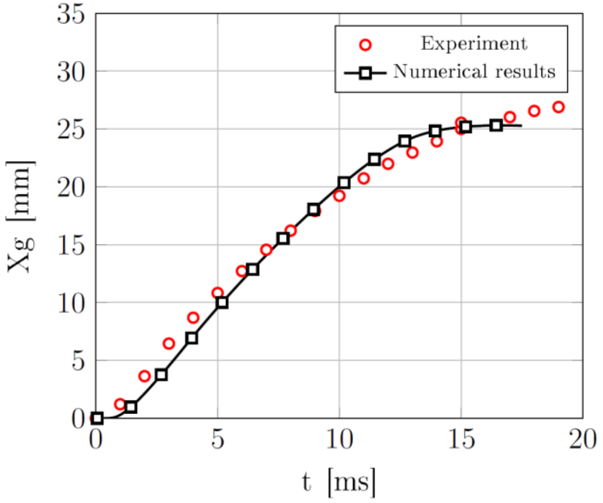

Figure 6. Gun position in time during the gun recoil

Based on the good agreement between numerical and experimental results, it can be concluded that the numerical simulation of the gun recoil process can provide the change of the thermodynamic properties that agree well with the real ones. Also, it provides the dynamics of the gun. This allows further analysis of the parameters that affect the pressure distribution in time inside the hydraulic brake.

5. INFLUENTIAL PARAMETERS ON THE PRESSURE DISTRIBUTION

Since the analyzed gun is anti-aircraft, the elevation angle of the gun usage is in the wide range. The reason for the analysis of the elevation angle influence on the pressure change inside the hydraulic brake is that the brake is not completely filled with oil. Therefore, the change of the elevation angle will cause the change of the mutual position of the oil free surface and the piston forehead. The numerical simulations, results of the oil pressure change with respect to time at different elevation angles are shown in figure 7. Three elevation angles: $\varphi = 0°$, $\varphi = 45°$ and $\varphi = 83°$ were taken into consideration. Since there is no significant pressure change inside the hydraulic brake until the entire piston forehead is in the contact with oil, i.e. until the oil flows through all 4 slots (both grooves in 2D geometry), it can be seen in the Figure 7. that elevation angle affect the maximum pressure that occurs in the brake during the recoil of the gun as well as the time when maximum pressure occurs. When the elevation angle is 83°, the first pressure peak (4.7 bar) occurs after 5 ms. At this moment oil starts to flow through all grooves. The velocity of the piston is 2.5 m/s, but the area of the flow surface is big since the recoil length of the piston is small. The second pressure peak (4.5 bar) corresponds to the moment (t=14 ms) when the piston forehead passes by the whole grooves. The velocity of the piston is 0.5 m/s, but ~~the~~ oil flows only through the gap between the piston and the bushing. Described pressure jumps occur in the hydraulic brake at the elevation angle $\varphi = 0°$, but at a different time and pressure values. The first peak (5.1 bar) occurs after 11 ms at the piston velocity 1.5 m/s and the second peak (7.2 bar) occurs at 13 ms (the velocity of the piston is 0.8 m/s). As it can be seen from the figure, the pressure has even distribution in time when the gun fires under the elevation angle $\varphi = 45°$. There is no peak when the piston passes by the groove end because the velocity of the piston is relatively small (0.5 m/s). In all analyzed cases, the recoil time is about the same (17 ms).

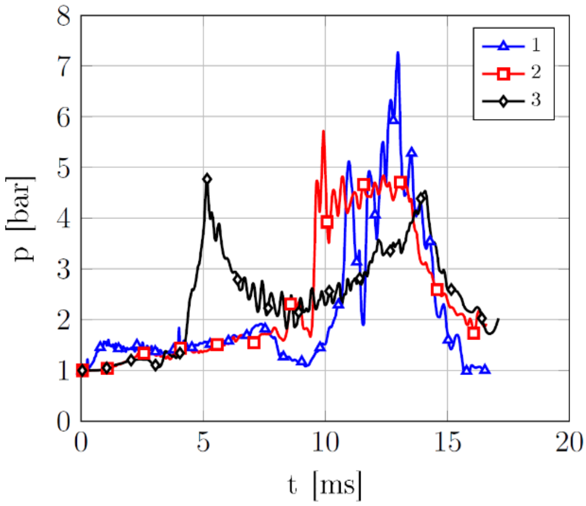

Figure 7. Pressure change in time at different elevation angles: 1-$\varphi = 0°$; 2-$\varphi = 45°$; 3-$\varphi = 83°$;

Since the oil properties depend on the temperature, it was analyzed the pressure distribution at different initial temperatures. The considered temperatures were 243K, 288K and 323K. The numerical simulation was performed under the assumption that the hydraulic brake was filled with the oil before the firing. This results that in every analyzed case there is the same volume of the oil, but with different density. Density depends on the thermal expansion coefficient. The value of this coefficient, as well as the other physical properties of the hydraulic oil, can be found in [8]. The results of the numerical simulation of the pressure distribution in time are shown in Figure 8. As can be seen in the figure, the hydraulic resistance begins approximately 1 ms earlier at extreme temperatures than at the normal one. When the initial temperature of the hydraulic brake is 323 K, the maximum pressure reaches 12.2 bar after 11.8 ms. At that moment, the piston is at the end of the grooves with the velocity of 1 m/s. The reason of this high velocity is reduced density and small resistance of brake until that moment. At the lower extreme temperature (243 K), the maximum pressure is 7.2 bar. As can be seen from the diagram, the pressure change at lower temperature is more even during time. The velocity change of the gun at the moment after breech block unlocking, at the extreme temperatures, can be neglected.

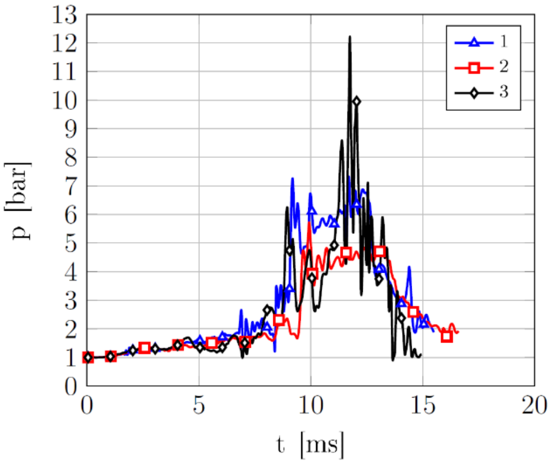

Figure 8. Pressure change in time at different initial temperature: 1-T=243K; 2-T=288K; 3-T=323K;

In Figure 9. is shown the mean temperature change of the oil during the recoil process at observed initial temperatures. The oil temperature change occurs due to viscous heating and heat transfer from the compressed air. From the diagram can be seen that for all analyzed initial temperatures, the temperature change of the oil will be between 0.4K and 0.7K. This temperature rise doesn't have a significant influence on the oil physical properties during one shot. For the burst fire it can be significant, but it also requires the analysis of the counter-recoil of the gun.

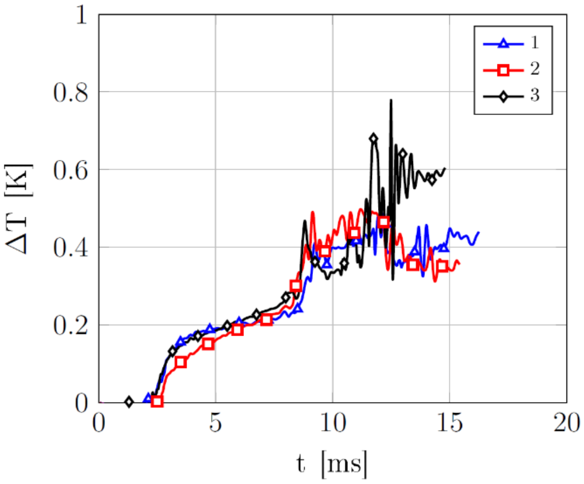

Figure 9. Temperature change of the air and the oil during the gun recoil: 1-T=243K; 2-T=288K; 3-T=323K

The amount of oil in the hydraulic brake also has an influence on the pressure distribution in time. This influence was studied using numerical simulation with three amounts of the oil that were taken into consideration: decreased 20%, normal and increased by 20%. The results are shown in Figure 10. Maximum pressure (5 bar), when the amount of the oil is increased (black curve on the diagram), was reached after approximately 7 ms. With the normal amount of oil, the maximum pressure has about the same value, but it was reached after 10 ms. If the oil volume is decreased (blue curve on the diagram), the great pressure jump will occur. The maximum pressure (35 bar) is reached after approximately 11 ms. The velocity of the piston (2 m/s) at the moment when maximum pressure occurs have approximately the same value for the cases when the oil volume is increased and decreased. The main reason for the high pressure value is the position of the piston when it occurs, i.e. the size of the flow surface.

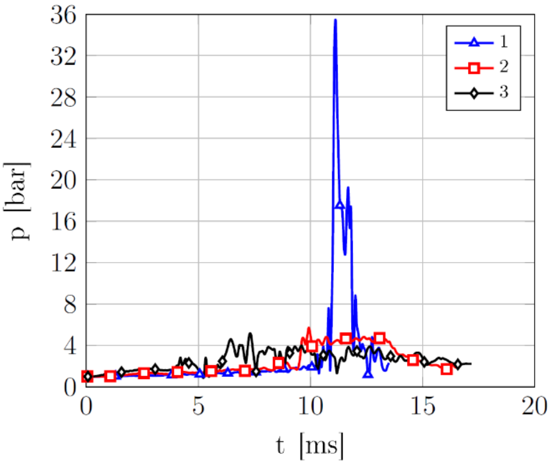

Figure 10. Pressure change in time at different hydraulic oil amount: 1-the oil amount reduced by 20%; 2-normal oil amount; 3- oil amount increased by 20%;

In Figure 11. is presented the density distribution inside the hydraulic brake at the moment when maximum pressure occurs when the amount of hydraulic oil is decreased.

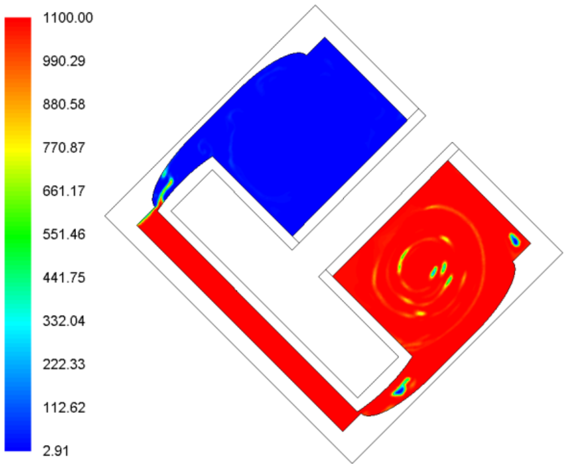

Figure 11. Density distribution in the hydraulic brake at the moment of reaching the maximum pressure ($\varphi = 45°$, T=288K, the amount of the oil decreased 20%)

As can be seen in the figure, the pressure jump is reached when the piston forehead passes by the whole slot length, so the flow area is the gap between the piston and the inner surface of the bushing. The increase of the oil amount has neglected influence on the recoil time. Since the hydraulic resistance starts earlier than in the normal case, the velocity of the gun at the moment of the breech block opening decrease by 0.25 m/s. Decreasing of the oil volume affects decreasing of the recoil time for about 4ms. The velocity of the gun at the breech block opening moment was increased by 0.5 m/s. The analysis was made to see what is the influence of the dimensions of the slot on the bushing (Figure 1) of the hydraulic brake on the pressure change in time that acts on the piston forehead. The first analyzed case consists of the slots with a 20% smaller width than the normal slots. The length of the flat part of the slot was unchanged. According to the slot width decrease, the radius at the ends of the slot also decreases as well as the length of the slot. The second analyzed case consists of the bushing on which the flat part of the slot was decreased by 46%. All other dimensions were unchanged. The length change of the flat part was made so that the lengths of the slot were equal in both cases. In figure 12. are shown the results of the numerical simulation. It can be seen on the diagram that maximum pressure (12.3 bar), when the slot width is decreased, occurs after 9 ms. The piston velocity at this moment is 1.8 m/s. The recoil time is 14.2 ms. When the flat part of the slots is decreased, the maximum pressure (11.9 bar) occurs after 11 ms. The piston velocity is 0.93 m/s. The recoil time, in this case, is 13.5 ms. In both cases, the velocity of the gun at the moment of breech block unlocking decrease the gun velocity for about 0.2 m/s.

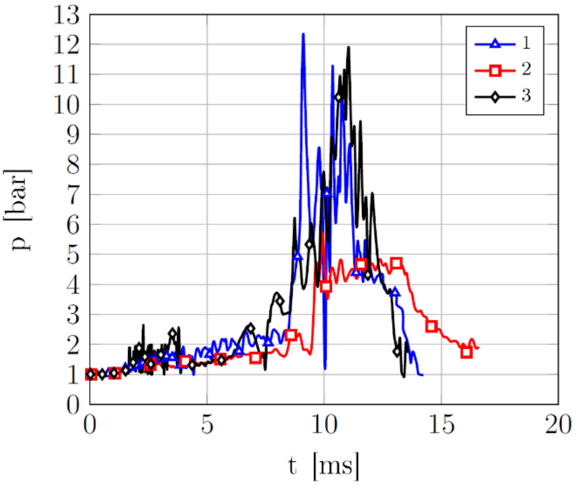

Figure 12. The influence of the slot size on the pressure change in time: 1- slot width decreased by 20%; 2-normal slot; 3- flat part of the slot decreased by 46%;

CONCLUSIONS

To analyze how does the design parameters of the hydraulic brake, elevation angle of the cannon and properties of the hydraulic oil affect the pressure inside the brake, numerical simulation was performed. The simulation was done in the 2D geometry domain which was created based on the flow geometry in 3D. Experimental results were obtained by firing 20 mm M55 gun on the proving ground. The experimental results consist of pressure change in the brake during the gun recoil measured with the piezoelectric sensor and the recoil length change recorded with the high-speed camera. Numerical results deviate in acceptable limits with respect to the experimental results. The numerical simulation shows that the elevation angle has an influence on the pressure distribution in time. Three analyzed cases ($\varphi = 0°$; $\varphi = 45°$; $\varphi = 83°$;) show that decreasing elevation angle produces lower maximum pressure and even pressure distribution in time. It has no significant influence on the recoil time. The analysis of the initial temperature of the hydraulic brake may affect the pressure on the piston forehead. Lower temperature produces higher maximum pressure than the normal temperature. The pressure distribution is even. Higher temperature causes higher values of the maximum pressures, but only in peak. The pressure distribution is less even than at the normal temperature. Both extreme temperatures cause the recoil time to decrease. It shows that the greatest influence on the pressure in the brake has the amount of oil. Increasing the oil volume produces lower maximum pressure and more even pressure change in time. Decreasing of the oil amount cause the sudden pressure jump of the great intensity. As a consequence of that, the recoil time is decreased. The increase of the oil amount will reduce the gun velocity at the breech block opening moment, while the smaller amount of the oil will increase it. It was analyzed the influence of the design parameters of the bushing slots on the pressure distribution. The analysis shows that a decrease of the slot width as well as the decrease of its length will cause a higher maximum pressure than the normal slot. It also causes a decrease in recoil time. These changes will decrease the velocity of the gun at the moment of the breech block unlocking, which can have an influence on the fire rate.

REFERENCES

[1] D. Jevtić, D. Micković, S. Jaramaz, P. Elek and M. Marković, "The Influence of the Temperature Change on the Force in the Hydraulic Brake of the Artillery System," in *19th Conference on Thermal Science and Engineering of Serbia*, Sokobanja, Serbia, 2019.

[2] S. Peng, C. Zhou and C. Yu, "The Numerical Simulation of Three-Dimensional Dynamic-mesh Flow Field of a hydraulic buffer," *Advanced Materials Research*, Vols. 588-589, pp. 1264-1268, 2012.

[3] S. Yezun, Q. Junqi, D. Changchun, C. Kaibo and W. Yan, "Simulation Analysis on Interior Flow Field of Recoil Brake Based on Dynamic Mesh," *Advanced Materials Research*, Vols. 765-767, pp. 427-430, 2013.

[4] ANSYS Fluent UDF Manual, ANSYS Inc, 275 Technology Drive Canonsburg, PA 15317, January 2015.

[5] D. Micković, "A Method of interior ballistic cycle computation (KGRAD code)" [in serbian], Technical report No. ME-0253, Faculty of Mechanical Engineering, Belgrade, Serbia, 2002.

[6] T. J. Chung, Computational fluid dynamics, Press Syndicate of the University of Cambridge, Cambridge, United Kingdom, 2002.

[7] A. H. Куприянов, "Основы проектирования артиллерийских орудий - Проектирование противооткатных устройств", Пенза, 1960.

[8] A. A. Толочков, "Теория лафетов артиллерийских установок", Государственное научно-техническое издательство Оборонгиз, Москва, 1960.