ANALYSIS OF PARAMETERS INFLUENCING THE PRESSURE AND TEMPERATURE DISTRIBUTION IN THE GUN BORE EVACUATOR

by

Miloš D. MARKOVIĆ[a*] Predrag M. ELEK[a], Dragana D. JARAMAZ[b], Dejan T. JEVTIĆ[a], Radovan V. DJUROVIĆ[a], Lana S. JARAMAZ[c], and Dušan D. MICKOVIĆ[d]

[a] Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia
[b] University Union - Nikola Tesla, Belgrade, Serbia
[c] Innovation Center, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia
[d] EDePro, Belgrade, Serbia

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The purpose of a gun bore evacuator on the turret-mounted gun barrel is to prevent the entry of the gaseous products of gun propellant combustion into the turret compartment of the vehicle after the breech block opening. The mathematical model which takes into account all of the main parameters influencing the pressure change inside the cylinder of the evacuator was developed. Differential equations that describe the flow field through the nozzle in the barrel wall and in the cylinder of the evacuator were solved numerically. Furthermore, the numerical simulations were performed using the ANSYS FLUENT in order to analyze the phenomena occuring in the evacuator during the charge and discharge cycles which are difficult to be taken into account with the analytical model. Aforementioned simulations were performed with the 3-D model of the evacuator and with the initial and boundary conditions obtained from the interior ballistic calculations. In order to find the change of the static pressure in the cylinder of the gun bore evacuator, the experimental research was performed. The comprehensive comparison between the numerical results and the experimental data has shown good agreement. Based upon this analysis, the influence of the evacuator's main design parameters on the pressure distribution and the temperatures in the critical zones was determined. The influence of the propellant's initial temperature on the pressure and wall temperatures in the evacuator was also analyzed, due to the wide range of gun operating temperatures and the possibility of erosion occurrence.

Key words: *gun bore evacuator, analytical model, CFD analysis, temperature distribution, pressure measurement*

Introduction

The gun bore evacuator represents the device whose purpose is to prevent the gunpowder combustion products from entering the turret compartment after the breech block opening. Although the design of the bore evacuator is rather simple, the number of factors which influence its functionality is substantial. Some of these factors are: the position of the bore evacuator along the gun barrel, the number and diameter of the nozzles, the inclination angle of the nozzle axis to the barrel axis, the volume of the gun bore evacuator, *etc*. Their influence on

* Corresponding author, e-mail: mdmarkovic@mas.bg.ac.rs

the flow field was analyzed in [1]. The design parameters which affect the turning of the gas-flow into the side orifice from the barrel are studied in [2, 3]. Also, the ambient temperature can affect the proper work of this device. The scope of this paper was to analyze how these factors affect the mean pressure change in the cylinder of the gun bore evacuator while the propellant gases are still in the barrel. Selected time period comprises all of the most important phenomena of the gun bore evacuator's operational cycle, including the entire process of its charge and discharge cycles. Change of pressure in the evacuator's cylinder was analyzed as it is the main thermodynamic parameter influencing the proper functionality of the complete device. Analytical model used in this analysis is simplified and does not take into account all the phenomena which occur in the nozzle and the cylinder. The main simplification is that the energy loss was analyzed only for two extreme cases: with maximum possible heat transfer and without the heat transfer at all. For the more detailed insight into the change of thermodynamic properties during the charge and discharge cycles, the numerical analysis was conducted using the ANSYS FLUENT. Afterwards, the results from the numerical simulations were compared and verified with the experimental data on the pressure change in time, obtained during the 105 mm tank gun firings on the proving ground. The comparative analysis between numerical results and experimental data has shown good agreement and based upon that, the assumption was made that all the other numerically simulated processes in the gun bore evacuator will correspond to the real ones. Furthermore, it was found that the analytical model gives the mean pressure change in the cylinder with satisfying accuracy. The temperature distribution in the barrel wall as well as in the evacuator cylinder was also analyzed, revealing the critical zones for the occurrence of erosion.

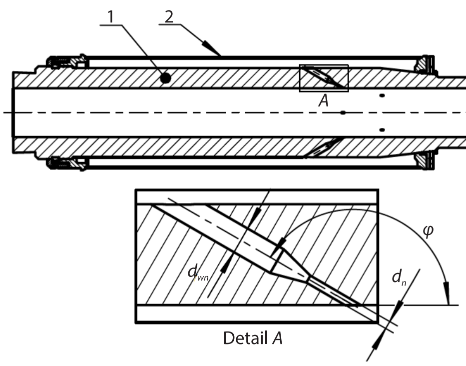

Figure 1. Cross-section of the gun barrel and gun bore evacuator: *1 – gun barrel and 2 – gun bore evacuator*

Analytical model

With the projectile passing by the nozzles in the gun barrel wall, fig. 1, the propellant gases will start entering the cylinder of the evacuator. The change of the mean pressure in the cylinder of the evacuator can be determined using the eq. (1) [4], based on the first law of thermodynamics for the open system:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{\kappa - 1}{W}\left[\dot{m}_{\mathrm{in}} h_{\mathrm{in}} - \dot{m}_{\mathrm{out}} h_{\mathrm{out}} - \frac{\mathrm{d}Q}{\mathrm{d}t} - \frac{\kappa}{\kappa - 1} p \frac{\mathrm{d}W}{\mathrm{d}t}\right] \tag{1}$$

While the ratio of the pressures in the cylinder of the gun bore evacuator and the barrel is below the critical value (which is 0.5549 for the gunpowder gases), mass-flow rate through the nozzle critical cross-section, fig. 2, can be evaluated using the following equation [5, 6]:

$$\dot{m}_n = C_{D,n}\, \xi_n\, n_n \frac{d_n^2 \pi}{4} \sqrt{\kappa \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa+1}{\kappa-1}}} \frac{p_{x,n}}{\sqrt{\mathrm{R_g} T_{x,n}}} \tag{2}$$

During the period of further projectile's movement through the barrel and the barrel emptying process, the pressure in the barrel decreases while in the nozzle it increases. As a result, the pressure ratio will become equal with the critical value, after which it will be possible to calculate the mass-flow through the nozzle critical cross-section using the following equation [5, 6]:

$$\dot{m}_n = C_{D,n}\xi_n n_n \frac{d_n^2\pi}{4}\sqrt{\frac{2\kappa}{\kappa-1}\mathrm{R_g}T_{x,n}\left[\left(\frac{p_{\mathrm{gbe}}}{p_{x,n}}\right)^{2/\kappa}-\left(\frac{p_{\mathrm{gbe}}}{p_{x,n}}\right)^{\frac{\kappa+1}{\kappa}}\right]} \tag{3}$$

Due to the high velocity of the gases and their inertia, they are not able to turn immediately into the nozzle. As a result, a re-circulation zone is formed at the nozzle entrance wall which is closer to the gun breech block. This re-circulation zone reduces the flow surface of the nozzle inlet, (which can be seen in fig. 2). This way, the size of the re-circulation zone directly affects the mass-flow in both flow regimes. The flow parameters in the gun barrel affect the size of this zone and they are taken into account with the discharge coefficient, $C_{D,n}$ [7]. The values of the discharge coefficient that are given in [7] correspond to the nozzle angle of $\varphi = 90°$. For the nozzle inclination angle greater than 90°, the discharge coefficient must be multiplied with the correction coefficient, ξ_n. To simplify the analytical model, the mean pressure change during the charge and discharge cycles was analyzed in two extreme cases using the EVAC code [5, 6]. The first case is without the heat transfer between the propellant gases, the nozzles and the cylinder walls. The second case is with the heat transfer included. In the latter case, the heat transfer is maximized because it is assumed that the wall temperature is constant and equal to the ambient temperature during the entire process. Determination of the specific heat transfer coefficient was described in [8].

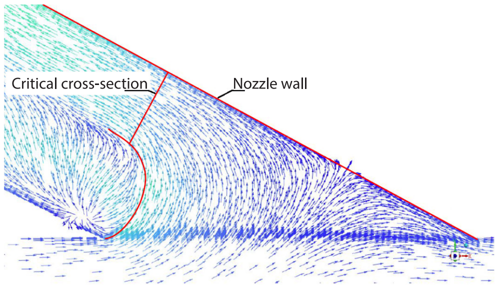

Figure 2. Re-circulation zone at the nozzle entrance

The last term in the brackets on the right-hand side of the eq. (1) is equal to zero due to the cylinder volume being constant. Following the equalization of the pressures in the cylinder of the evacuator and the barrel, the discharge cycle begins with the mass-flow through the nozzle that can be determined using eq. (3). Due to the fast pressure drop in the gun barrel, the flow through the nozzle enters the critical flow regime, in which the mass-flow can be determined using eq. (2). During the discharge cycle, the coefficient $C_{D,n}$ has a different value and it needs not to be multiplied by the correction coefficient ξ_n.

Numerical simulation

Thermodynamic properties of the propellant gases inside the evacuator and their change in time were calculated by the means of numerical simulation performed in the ANSYS FLUENT. Although the 3-D model of the device was used, the fact that the evacuator has four symmetry planes was utilized making it possible to conduct the simulation on the 1/8 of the real device, which is shown in fig. 3. In order to decrease the number of elements of the numerical mesh, thicknesses of the metal walls around the nozzles, the barrel and the evacuator were minimized. This is justified due to the short duration of the observed processes during which only a thin layer of walls gets heated. The initial time for numerical simulation is the moment in

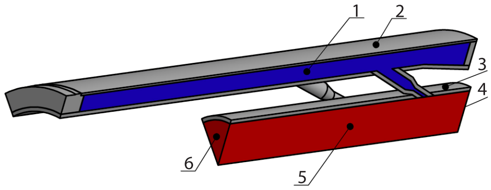

Figure 3. Numerical domain: *1 – air, 2 – gun bore evacuator cylinder, 3 – gun barrel, 4 – outlet boundary, 5 – propellant gases, and 6 – inlet boundary*

which the projectile's bottom reaches the outlet boundary of the numerical domain, fig. 3. The realizable k-ε model with scalable wall functions was used to describe the turbulent flow.

The viscous heating was taken into account. The coupled numerical scheme was used for solving the equations that describe the flow field. Although the flow occurs in the strongly curved domain, the pressure field was obtained using second order spatial discretization instead of PRESTO. The second order discretization scheme uses the solution from the cell center to determine the pressure on the cell face according to the Taylor series expansion. In order to reduce the error of the pressure which acts on the cell face at the nozzle entrance, the height of the cell at that zone is created using the inflation layers, fig. 4.

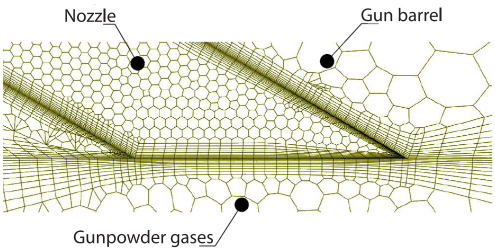

Figure 4. Numerical mesh on the symmetry plane

Also, these layers were applied to all boundary surfaces between gases and metal parts for better simulation of the boundary-layer and heat transfer. The numerical mesh consists of approximately 3.5 million polyhedral cells. The specific heat capacity at constant pressure can be obtained based on thermochemical calculations of composition of propellant gases under standard conditions [9]:

$$c_p = 0.1059T + 1533 \tag{4}$$

The dynamic viscosity of propellant gases can be written using Sutherland's equation [10]:

$$\mu_\mathrm{g} = 1.458 \cdot 10^{-6} \frac{T_\mathrm{g}^{1.5}}{T_\mathrm{g} + 110.3} \tag{5}$$

Dependence of the thermal conductivity of the combustion gas products on temperature can be written in the following form [11]:

$$\lambda_\mathrm{g} = 1.317\mu_\mathrm{g}\left(T_\mathrm{g}\right)\left[\frac{3540}{M} + c_p\left(T_\mathrm{g}\right)\right] \tag{6}$$

Thermal rad iation was taken into account by using the discrete ordinates model. Although at the beginning of the bore evacuator charge cycle, the difference between gases and wall temperatures is large, the main heat transfer mechanism in the nozzle is forced convection due to the high flow rates inside the nozzle. The nozzle side closer to the gun barrel muzzle is the stagnation point for the gasses in the barrel. On the opposite side of the nozzle, the re-circulation zone occurs with dominant turbulent flow [12] with enhanced heat transfer coefficient [13]. The maximum temperature on the gun barrel outer surface is located in the vicinity of the nozzle opening due to the vortex zone that occurs there. Near the bottom of the evacuator cylinder which is closer to the breech block, the heat transfer caused by forced convection is small due to low values of the gas velocity in that zone. However, the heat transfer due to radiation can also be neglected because the gas temperature near that surface is below 900 K. Based on this analysis, it can be concluded that the radiation does not have a significant influence on the maximum temperatures at the critical zones of the evacuator and the barrel and therefore, it will not be taken into consideration in further analysis. The change of pressure, velocity and temperature of the gases at the inlet boundary (which is defined as velocity-inlet in FLUENT) during the barrel discharging process is shown in the figs. 5(a)-5(c), respectively. At the outlet boundary (which is defined as pressure-outlet in FLUENT), the change of pressure and temperature over time is shown in figs. 6(a) and 6(b), respectively. Also, the change of pressure and temperature for two cases of extreme propellant charge temperature (243 K and 323 K) may be seen in the same figures. All the input data on boundaries as well as the distribution of the pressure, temperature, and velocity of the gases in the barrel at the initial time were obtained from interior ballistic calculations [14].

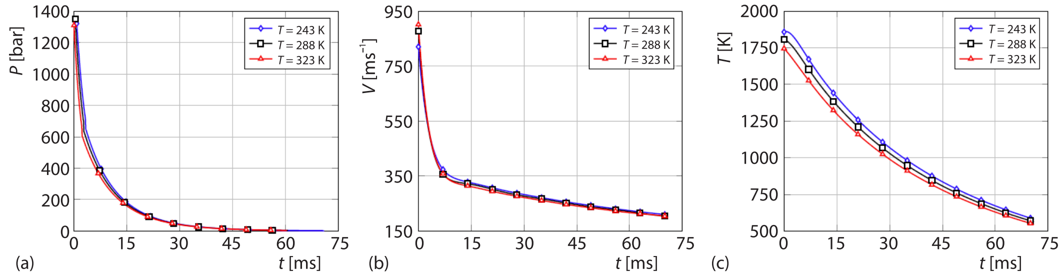

Figure 5. Boundary conditions change in time at the inlet boundary at different propellant charge temperatures; (a) pressure, (b) velocity, and (c) temperature

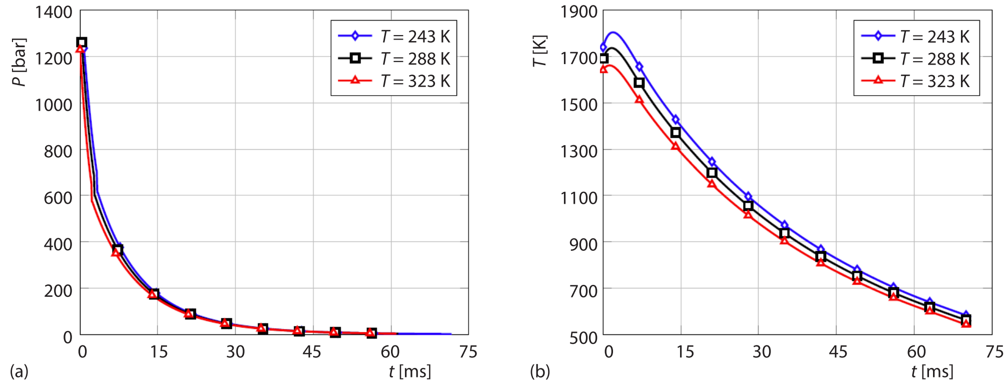

Figure 6. Boundary conditions change in time at the outlet boundary at different propellant charge temperatures; (a) pressure and (b) temperature

Results and discussion

Experimental results of the pressure change over time in the bore evacuator with eight nozzles were obtained from the 105 mm gun firings on the proving ground, shown in fig. 7.

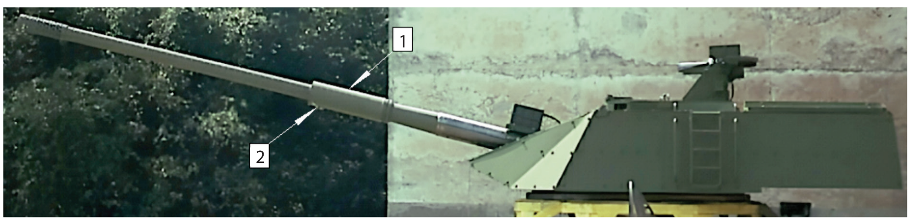

Figure 7. The 105 mm gun on the proving ground: *1 – gun bore evacuator and 2 – location of the piezoelectric pressure sensor*

The pressure of the gunpowder combustion gas products was measured using the piezoelectric pressure sensor KISTLER 6215, which was mounted in the cylinder wall. The

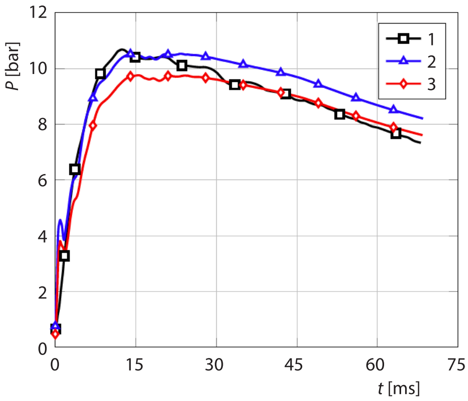

Figure 8. Pressure change in time at the pressure-gauge location: *1– experimental results, 2 – numerical simulation with the air in the evacuator, and 3 – numerical simulation without the air in the evacuator*

numerical analysis included two cases. In the first one, the projectile is at the outlet boundary (the initial moment for the simulation), while the evacuator and the nozzles are filled with the air only. Under the assumption that unburned gunpowder particles do not enter the nozzles, there is no combustion in the evacuator and the gas in it is a mixture of two gases without chemical reaction. This is modeled using species transport in ANSYS FLUENT. The second case implies that there is a certain amount of gunpowder gases in the gun bore evacuator at the moment in which the projectile is at the outlet boundary. This assumption is justified due to the wear of the driving band and the passage of gunpowder gases in front of the projectile as it moves through the barrel. The pressure sensor recorded the pressure increase of 0.2 bar before the projectile passed by the nozzle, but in this study that was neglected. The assumption was made that the gunpowder combustion products in the evacuator are at 1 bar and 288 K. The numerically and experimentally obtained pressure curves for both of the aforementioned cases, at the location of the piezo-gauge, are shown in fig. 8. The gases needed approximately 1.7 ms to reach the pressure sensor location, as it was seen from the numerical simulation results. With the aim to provide better comparative analysis with experimental data, the numerical curves were shifted so that the pressure change would start at the same time for all three curves. As it can be seen on the diagram, numerical simulation with the air in the evacuator has a good match with the experimental data until the maximum pressure is reached (approximately 10.5 bar after 13 ms). After 31 ms, the numerical pressure change has better agreement with experimental data for the simulation without the air in the bore evacuator. The pressure drop caused by the heat transfer from the gases to the metal walls is faster without the air in the evacuator, due to

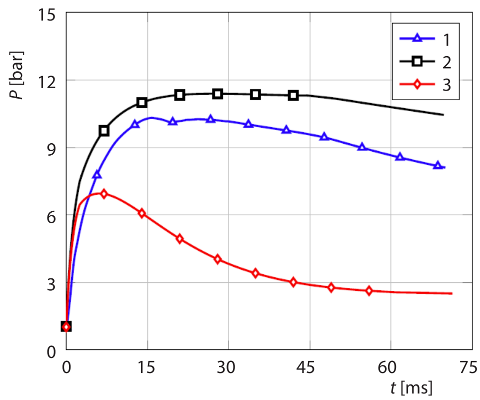

Figure 9. Mean pressure change over time in the gun bore evacuator: *1 – CFD analysis, 2 – EVAC code without heat transfer, and 3 – EVAC code with heat transfer*

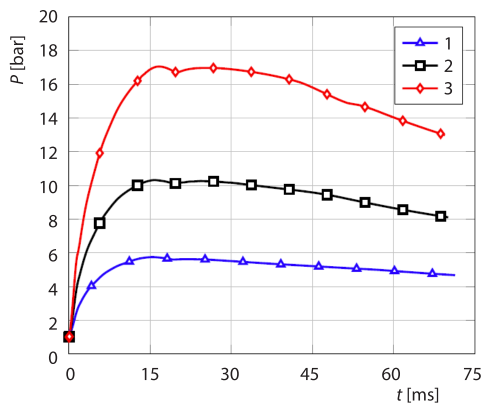

Figure 10. The influence of the nozzle diameter on the mean pressure in the gun bore evacuator: *1 – d_n = 2.5 mm, 2 – d_n = 3.5 mm, and 3 – d_n = 4.5 mm*

it having lower thermal conductivity than the combustion products. Therefore, further analyzes were performed without the air in the gun bore evacuator. Based on good agreement between the experimental and numerical pressure curves, the assumption can be made that the changes of all other thermodynamic properties of propellant gases in the evacuator cylinder correspond to the real values. The mean pressure changes in the cylinder according to the analytical model (with and without heat transfer) and numerical simulation are presented in fig. 9. The mean pressure change obtained by the analytical model is considerably closer to the results of numerical simulation when the heat transfer is not being taken into account. Although the heat transfer is intense, the short time period in which the value of the mean pressure is close to the maximal value makes it possible to neglect the heat transfer. When the maximum value is reached, the discharge cycle begins with a small value of the mass-flow through the nozzles. The main energy loss in this period is due to heat transfer, so pressure obtained by the analytical model without heat transfer remains constant. When the mass-flow through the nozzles increases, the pressure drop obtained by the analytical model and numerical simulation has the approximately same value. The mean pressure change over time (ANSYS FLUENT) inside the cylinder of the evacuator for different nozzle diameters is shown in fig. 10.

Nozzle diameters $d_n = 2.5$ mm, $d_n = 3.5$ mm, and $d_n = 4.5$ mm, were analyzed. As it can be seen from the diagram, the maximum pressure for each analyzed nozzle diameter is achieved at the approximately same time (13 ms). When the discharge cycle begins, it can be seen that the greater nozzle diameter causes a faster pressure drop. Based on this analysis, the conclusion can be made that increase in the nozzle diameter does not provide any particular advantages. The greater diameter will allow faster charging of the evacuator but also faster discharging which implies that at the moment of the breech block opening (~700 ms), the cylinder contains almost the same amount of gases for all of the observed cases. The change of the nozzle's maximum temperature due to the change in its diameter can be seen in fig. 11(a). The maximum temperature reaches the value of 1680 K after approximately 1 ms and it is not being significantly influenced by the variations of the nozzle diameter. Also, the numerical simulation has shown that the influence of the nozzle inclination angle and initial temperature on the maximum nozzle temperature over time can be neglected, so they will not be further discussed in this paper. However, variation of the nozzle diameter affects the temperature of the evacuator cylinder's inner surface, which is shown in fig. 11(b). A larger nozzle diameter allows larger mass-flow at the nozzle entrance with the gas temperature being unchanged. An increase in energy losses

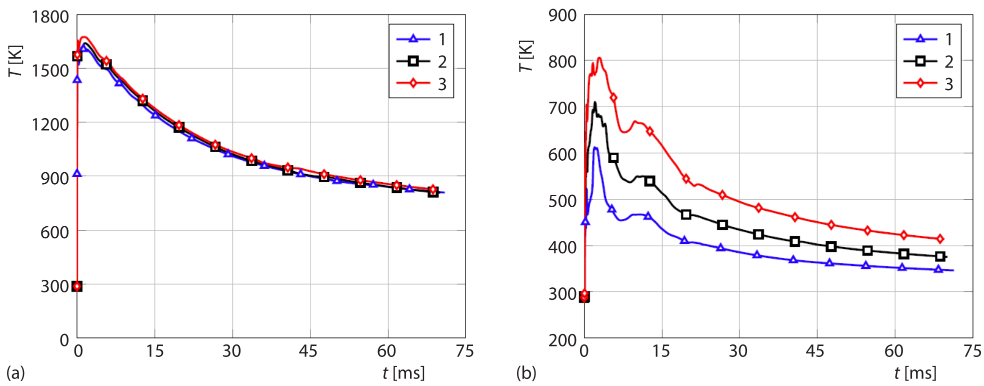

Figure 11. The influence of the nozzle diameter (*1 – d_n = 2. 5 mm, 2 – d_n = 3.5 mm, and 3 – d_n = 4.5 mm*) on the maximum temperature, (a) nozzle and (b) inner surface of the evacuator cylinder

due to an increase of the nozzle surface through which the heat is transferred can be neglected. Since the nozzle opening diameter at the outer barrel surface had the same value for all of the analyzed cases, this produced less gas expansion in the wider part of the nozzle (diameter d_{wn}, fig. 1), *i.e.* smaller drop of the gas static temperature at the bore evacuator entrance (approx. increase of 100 K for a nozzle with d_n = 4.5 mm compared to the nozzle with d_n = 3.5 mm). The gas velocity is negligibly smaller at the evacuator's entrance in the case of a nozzle with a larger diameter. and the Mach number decrease. Numerical simulation has shown that the increased static temperature has more influence than the decreased Mach number and consequently, the total temperature at the cylinder entrance is higher when the nozzle diameter is larger. Larger mass-flow will cause reduced expansion of gases after they exit the nozzle, *i.e.* higher total temperature of the gases near the surface of the evacuator cylinder. As a result, the larger value of the nozzle diameter will induce a higher maximum temperature of the evacuator cylinder. The higher temperature gradient in the cylinder wall will cause a faster drop of the maximum temperature which means that the nozzle diameter does not have significant influence on the cylinder's wall temperature prior to the firing of the next round.

At the start of the evacuator's charge cycle, the gases in the barrel have high velocity and pressure while the pressure in the nozzle is small. Since the nozzle entrance diameter is small, a certain amount of gases does not have enough space to completely turn into the nozzle and due to that, they will hit the part of the nozzle's wall which is closer to the barrel's muzzle. That side of the nozzle's wall represents the stagnation point.

The velocity vector field in the nozzle and the position of the stagnation point can be seen in fig. 12. The distribution of the temperature at the nozzle inner wall in the moment in which the maximum temperature is reached is shown in the fig. 13(a). At the end of the gun barrel discharge cycle, fig. 13(b), the maximum temperature (830 K) occurs at the part of the surface closer to the breech block. This means that the entire nozzle entrance opening edge represents the critical zone for erosion. The influence of the nozzle inclination angle on the mean pressure change (ANSYS FLUENT) is shown in fig. 14(a). The nozzles inclination angles φ = 145°, φ = 150°, and φ = 155° were taken into consideration. As it can be seen from the fig. 14(a), the increase of the angle between the nozzle axis and the gun barrel axis reduces the maximum value of the pressure.

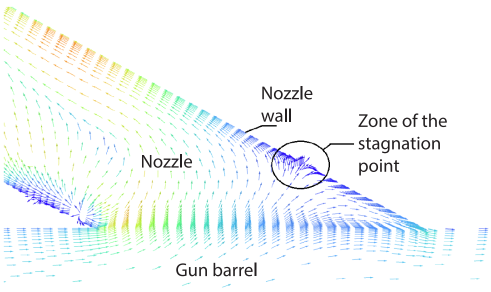

Figure 12. Velocity vector field and the stagnation point

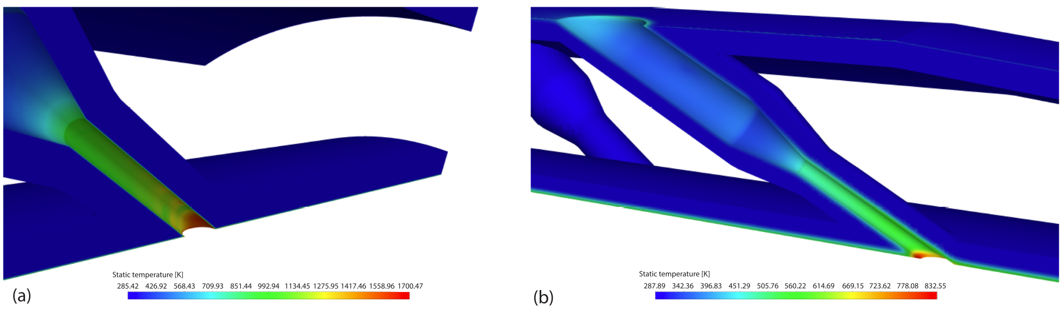

Figure 13. Temperature distribution in the nozzle; (a) when the maximum temperature is reached and (b) at the end of the gun barrel discharge

Numerical simulation has shown that the increase of the nozzle's axis inclination angle is going to produce a higher ratio between the re-circulation zone's surface area at its widest part and the nozzle's cross-section area, meaning that the nozzle's flow area decreases with the increase in the nozzle's inclination angle. Since the ratio of the pressures in the cylinder and the barrel is below the critical value for most of the charging period of the evacuator, the velocity of the gases at the smallest cross-section area of the nozzle is equal to the local speed of sound. If the energy loss from the nozzle entrance to the critical cross-section of the nozzle is neglected, the local speed of sound at the critical cross-section depends only on the temperature of the gases in the barrel at the position of the nozzle entrance. This assumption is justified due to the distance between these two surfaces being small. During the discharge cycle, pressure drop for all three inclination angles is the same, since during that period there is no re-circulation zone in the nozzle. According to this, it seems that increase of the nozzle inclination angle over φ = 150° has negative influence on the proper function of the gun bore evacuator. However, only calculations of air evacuation from the turret will enable a relevant conclusion. The diagram in fig. 14(b) shows the maximum temperature change of the evacuator cylinder's inner surface. Since the ratio of smaller and larger nozzle diameter, fig. 1, is the same for all of the analyzed inclination angles, there is a small variation in the gas static temperature and velocity at the nozzle's outer surface during the charge cycle of the evacuator cylinder.

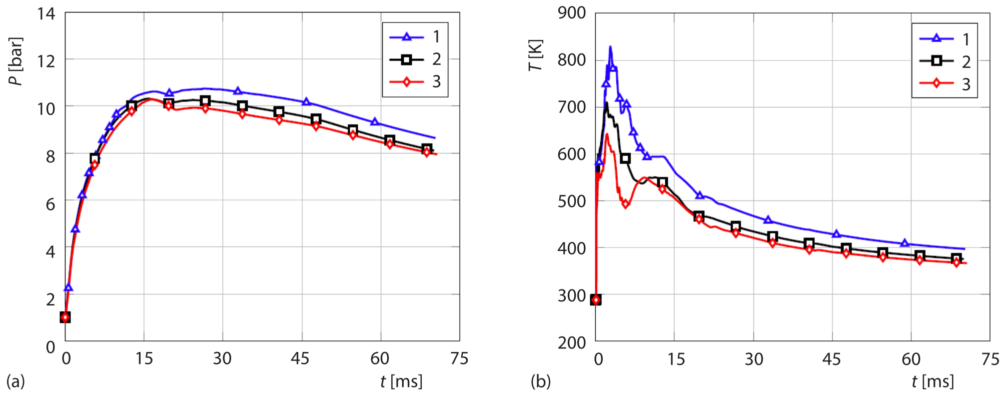

Figure 14. The influence of the nozzle inclination angle (*1 – φ = 145°, 2 – φ = 150°, and 3 – φ = 155°*) on: (a) the mean pressure in the bore evacuator and (b) the maximum temperature of the evacuator cylinder inner surface

However, the larger mass-flow at the lower inclination angle produces a higher value of the gas total temperature near the cylinder wall surface and a higher value of the maximum wall temperature. The faster drop of the maximum temperature will occur with the smaller inclination angle of the nozzle, *i.e.* the influence of the nozzle inclination angle on the cylinder wall temperature before the next round is fired can be neglected. Since the temperature interval of the gun usage is wide, it is necessary to analyze the functionality of the gun bore evacuator within the limits of that interval. The numerical simulation results of the mean pressure changes in the bore evacuator at different propellant charge temperatures (T = 243 K, T = 288 K, and T = 323 K) are presented in fig. 15(a). The maximum pressure values for all three analyzed temperatures has been reached almost at the same time, while the difference between maximum pressures at extreme temperatures is approximately 1 bar. In all of the analyzed cases, the pressure drop in the cylinder has the approximately same value which means that after some time the energy loss is equal for all temperatures. It can be concluded that the initial temperature of the propellant charge has a small influence on the functionality of the evacuator. The diagram in the fig. 15(b) shows the influence of the propellant's initial temperature on the temperature change at the inner surface of the evacuator cylinder. As it can be seen, its influence on the cylinder's surface maximum temperature is negligible. Higher temperature gradient in the cylinder's wall at the lower propellant's initial temperature causes a faster maximum temperature drop which may positively influence the temperature of the cylinder's wall, lowering it prior to the firing of the next round.

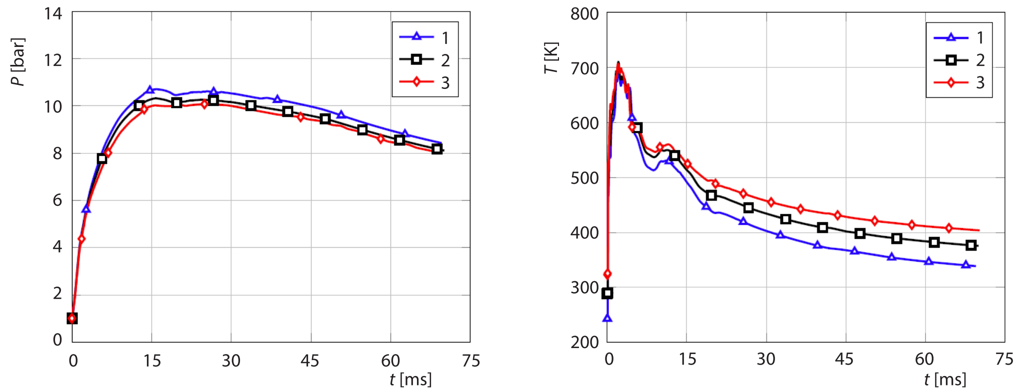

Figure 15. The influence of the propellant charge initial temperature (*1 – T = 243 K, 2 – T = 288 K, 3 – T = 323K***) on: (a) the mean pressure in the bore evacuator and (b) the maximum temperature of the evacuator cylinder inner surface**

Conclusions

In an effort to observe the influence of the main design parameters which affect the proper functionality of the evacuator, while also reducing the number of relatively expensive experiments in the early design phase, the analytical model was made. By utilizing it, the change of the pressure mean values in the evacuator can be determined. It was found that the analytical model which does not take into account the heat transfer at all gives considerably better predictions than the model where the heat transfer is maximized due to the wall temperature being assumed constant during the charge and discharge cycle. To analyze the phenomena which occur during the charge and discharge cycles of the evacuator, the numerical simulation in ANSYS FLUENT was performed. Results of such a simulation were verified with the experimental data from the 105 mm tank gun firings. Experimental results have shown the change of pressure over time in the cylinder of the evacuator, and a good agreement with the numerical results was achieved. Afterwards, the influence of the main design parameters on the pressure change in the evacuator was analyzed using the verified numerical model. According to the results of the simulation, it can be seen that the change of the nozzle diameter does not have a significant influence on the function of the evacuator. The larger nozzle diameter will cause a higher value of the maximum pressure but it will also cause the faster discharge of the evacuator. It seems that the increase of the nozzle inclination angle over 150° has a negative effect on the functionality of the device. Higher the value of the inclination angle is, smaller is the value of the maximum pressure and the amount of the gases in the cylinder. Thus, due to the rate of the cylinder discharge being independent on the nozzle inclination angle, the discharge of the evacuator will be completed earlier with a higher value of the inclination angle. However, calculations of air evacuation from the turret are necessary to enable a relevant predictions. The influence of the ambient temperature on the pressure change in time was also analyzed. Pressure changes were analyzed at the extreme propellant charge temperatures (243 K and 323 K) and at the normal temperature (288 K). The results obtained from the numerical simulations have shown that the influence of the ambient temperature on the functionality of the evacuator can be neglected. The change of the nozzle diameter and inclination angle as well as the propellant's initial temperature have negligible influence on maximum nozzle temperature while providing a significant influence on the maximum temperature of the evacuator cylinder which is a crucial parameter in the determination of the evacuator cylinder's diameter. It was concluded that the developed numerical simulation can be also successfully used in studying of complex flow phenomena, such as the calculation of the discharge coefficient.

Nomenclature

$C_{D,n}$ – discharge coefficient, [–]
c_p – specific heat capacity at constant pressure, [Jkg^{-1}K^{-1}]
d_n – nozzle diametar, [m]
d_{wn} – diametar of the nozzle wider part, [m]
h_{in} – specific enthalpy on the inlet urface, [Jkg^{-1}]
h_{out} – specific enthalpy on the outlet surface, [Jkg^{-1}]
M – molar mass of gasses, [kgmol^{-1}]
$\dot{m}_n$ – mass-flow rate in the nozzle, [kgs^{-1}]
$\dot{m}_{\mathrm{in}}$ – mass-flow rate in the inlet surface, [kgs^{-1}]
$\dot{m}_{\mathrm{out}}$ – mass-flow rate in the outlet surface, [kgs^{-1}]
n_n – number of nozzles, [–]
p_{gbe} – gas pressure in the gun bore evacuator, [Pa]
$p_{\mathrm{x,n}}$ – gas pressure in the berrel at the nozzle position, [Pa]
Q – heat transfer from gasses to wall, [J]
$\mathrm{R_g}$ – gas constant, [JK^{-1}mol^{-1}]
T_{g} – gas temperature, [K]
$T_{x,n}$ – gas temperature in the barrel at the nozzle position, [K]
W – volume of the evacuator cylinder, [m^3]

Greek symbols

κ – heat capacity ratio, [–]
λ_{g} – thermal conductivity of the gas, [Wm^{-1}K^{-1}]
μ_{g} – dinamyc viscosity of the gas, [Pa]
ξ_n – correction coefficient, [–]

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