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Prediction of the distribution and effect of diameters of the cylinder and the piston post-manufacture on the operation of gas-operated automatic rifles

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Abstract. Predicting the distribution of diameters of the cylinder inner and the piston outer post-manufacture is very important to improve the quality of the gun manufacturing process. However, it is not easy to find records related to this research. The article focuses on applying reliability and experimental statistics theory to predict the distribution of the cylinder inner diameter and the piston outer diameter post-manufacture for gas-operated automatic rifles. The influence of these dimensions on the operation of the automatic system was also studied. The influence issue was studied in five cases corresponding to the maximum, minimum, and most probable post-manufacture of the cylinder and the piston. The study object in the article is 7.62 mm AKM-1 rifles. Research results show that the cylinder inner diameter and the piston outer diameter post-manufacture of 7.62 mm AKM-1 rifles follow the normal distribution. The dynamic characteristics of the automatic system in all five cases investigated are entirely consistent with the current technical conditions for gun acceptance post-manufacture. The research results of the article can be used to establish technical conditions for new gun acceptance post-manufacture.

Keywords: reliability, experimental statistics, distribution, automatic system, gas-operated automatic rifles, cylinder and piston post-manufacture.

Classification numbers: 5.1.2, 5.4.2.

1. INTRODUCTION

Gas-operated automatic guns use the propellant gases taken from ports in the barrel bore to drive the automatic system, and the gas piston is the most frequently used system. This type consists of a cylinder connected through a gas port with the barrel bore and a piston positioned in a cylinder. For a gas piston type, when the projectile passes the gas vent, the propellant gases enter the cylinder, where they impart a force to the piston. This force is transmitted to the automatic system. Therefore, the clearance between the piston and the cylinder greatly affects the operation of the automatic system. This clearance (Δ) is formed by the connection between the cylinder inner (d_v) and the piston outer (d_p) (Figure 1), and it consists of two types: clearance is formed because of wear during firing and the initial clearance post-manufacture.

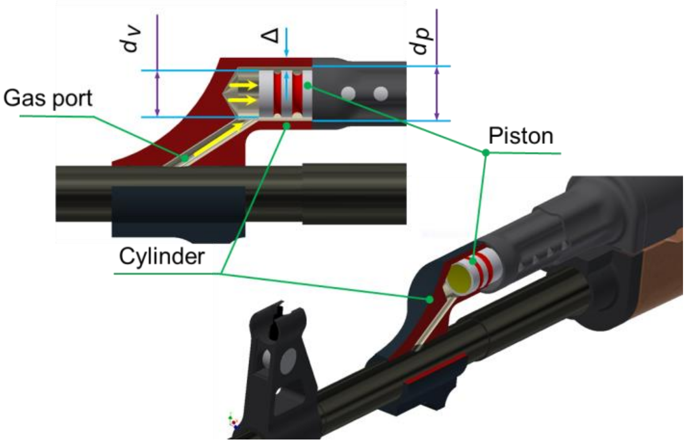

Figure 1. The clearance between the piston and the cylinder.

The clearance (Δ) formed because of wear during firing has been discussed by several scholars using a variety of methodological techniques, and they can be discussed as follows.

The research of Thanh [1] studies the effect of the clearance due to firing on the operation of a 7.62 mm PKMS machine gun. This study contributes to a better understanding of the dynamic characteristics under the influence of the clearance between the piston and the cylinder in firing. However, the research involved only the clearance formed because of wear during firing, with no initial clearance post-manufacture.

In the paper of Jevtic *et al.* [2], which deals with the numerical simulation with CFD software ANSYS Fluent was performed to analyze the change of the thermodynamic properties of the gases in the cylinder, temperature change of the cylinder parts, and dynamics of the gas piston. Besides, the experiment was performed to provide pressures in the barrel and the gas cylinder and the velocity of the gas piston. The comprehensive comparisons between results obtained by the analytical model, the numerical simulation, and experiments have been performed, and good agreements were observed.

The papers [3] and [4] study the firing stability of mounted small arms and the effects of breech bolt movement on the felt recoil of a gas-operated semi-automatic sporting gun. The research involved the clearance between the cylinder inner and the piston outer in firing.

In summary, many studies have been published on the clearance due to firing and the dynamic analysis of the gas-operated device. For the clearance in post-manufacturing, it is very important to predict the distribution of manufacturing accuracy. However, not much is known about the initial clearance post-manufacture. Currently, reliability theory is widely applied in many scientific disciplines. Nevertheless, the studies that have been published on the application of this theory to guns are very limited. So, this present study aims to predict the distribution of diameters of the cylinder inner and the piston outer post-manufacture. Besides, the effect of this initial clearance on the operation of the automatic system was studied. The primary object of this study is the 7.62 mm AKM-1 rifle shoots 7.62x39 mm ammo which was made by the technological process of Viet Nam.

2. PREDICTION OF THE DISTRIBUTION OF DIAMETERS OF THE CYLINDER INNER AND THE PISTON OUTER

2.1. Data collection

In order to predict the distribution of diameters of the cylinder inner and the piston outer, the investigation procedure was done on the 100 pistons and 100 cylinders of 7.62 mm AKM-1 rifles post-manufacture (Figure 2). This procedure is divided into three stages as follows.

a) *b)*

Figure 2. Pistons (a) and Cylinders (b) of 7.62 mm AKM-1 rifles post-manufacture were made by the technological process of Viet Nam.

Table 1. The outer diameter of 100 pistons in measurement (unit: μm).

13920	13923	13922	13925	13914	13923	13914	13928	13920	13922
13922	13925	13923	13913	13927	13926	13928	13923	13940	13920
13924	13919	13919	13920	13920	13912	13928	13927	13919	13918
13908	13920	13918	13925	13918	13920	13929	13918	13928	13929
13912	13924	13911	13920	13918	13928	13920	13927	13924	13933
13930	13914	13919	13924	13925	13921	13925	13925	13926	13905
13919	13910	13925	13922	13919	13927	13919	13927	13925	13935
13920	13924	13921	13921	13926	13923	13928	13928	13926	13922
13918	13908	13918	13922	13928	13920	13913	13920	13930	13918
13924	13914	13921	13926	13927	13922	13927	13921	13919	13923

Table 2. The inner diameters of 100 cylinders in measurement (unit: μm).

14011	14018	14002	14012	14014	14025	14017	14033	14013	14010
14019	14021	14022	14016	14010	14019	14026	14035	14017	14008
14016	14008	14021	14030	14027	14021	14021	14016	14017	14009
14019	14019	14021	14025	14029	14014	14021	14006	14025	14014
14016	14026	14028	14021	14026	14012	14018	14012	14020	14020
14013	14025	14015	14023	14026	14019	14025	14021	14022	14015
14018	14026	14030	14020	14019	14001	14019	14025	14005	14015
14030	14022	14029	14014	14016	14010	14020	14005	14021	14016
14016	14019	14019	14013	14017	14006	14030	14018	14020	14021
14006	14013	14009	14024	14017	14012	14000	14015	14021	14030

- The first stage measures the diameters of the cylinder inner and the piston outer post-manufacture.
- The second stage analyses and predicts the diameter distribution of the cylinder inner and the piston outer.
- The final stage validates the predicted rule.

The outer diameter of 100 pistons and the inner diameters of 100 cylinders in measurement are shown in Table 1 and Table 2.

2.2. Prediction of the distribution

The following section only shows the procedure for predicting the distribution of diameters of the piston outer; for the cylinder inner is performed the same procedure. To predict the distribution, we divide the data in Table 1 into 8 intervals, and the value of an interval is 4.375 µm according to the following formula [5]:

$$\begin{cases} k = 1 + 3.32.\lg 100 \approx 8 \\ \Delta d = \dfrac{d_{\max} - d_{\min}}{k} = 4.375\ (\mu m) \end{cases}$$

Table 3 and Figure 3 show the number of pistons and the frequency of appearance.

Table 3. Statistical estimation of the frequency of appearance of pistons for Δd = 4.375 µm.

Interval of piston outer diameter	Number of pistons $n(\Delta d)$	Frequency of appearance $h_i = \dfrac{n(\Delta d)}{n}$
13905 ÷ 13909.375	3	0.03
13909.375 ÷ 13913.75	6	0.06
13913.75÷ 13918.125	12	0.12
13918.125 ÷ 13922.5	32	0.32
13922.5 ÷ 13926.875	25	0.25
13926.875÷ 13931.25	18	0.18
13931.25÷ 13935.625	3	0.03
13935.625÷ 13940	1	0.01

From the graph in Figure 3, we can assume that the piston's outer diameter has a normal distribution. This hypothesis is verified by the Pearson – Romanovsky as presented below [6]:

By the above assumption, the general form of its probability density function is

$$f\left(x;\mu,\sigma\right)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (1)$$

where the parameter μ is the mean or expectation of the distribution, while the parameter σ is its standard deviation and

$$\begin{cases} \mu=\frac{1}{n}\sum_{i=1}^{n}x_i \\ \sigma^2=\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i-\mu\right)^2 \end{cases} \quad (2)$$

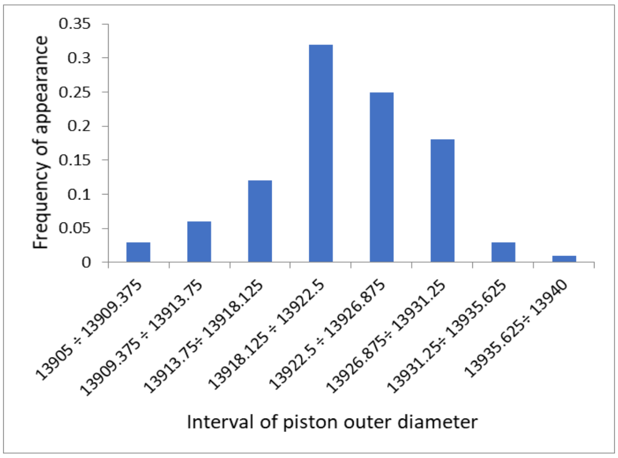

Figure 3. Relation between the interval of piston outer diameter and the frequency of appearance.

By substituting data in Table 1 into Eq.2, we obtain $\mu=13921.9\ \mu m$; $\sigma=5.77494$. The resulting integral to Eq.1 with the interval of piston outer diameter in Table 3 can be expressed in Table 4 [6].

Table 4. Distribution test data table of piston outer diameter.

Interval (Δd)	$n(\Delta d)$	$h_i=\frac{n(\Delta d)}{n}$	$p(\Delta d_i)$	$\frac{(h_i-p_i)^2}{p_i}$
13905 ÷ 13909.375	3	0.03	0.0138	0.019017
13909.375 ÷ 13913.75	6	0.06	0.0642	0.000275
13913.75÷ 13918.125	12	0.12	0.1746	0.017074
13918.125 ÷ 13922.5	32	0.32	0.2794	0.0059
13922.5 ÷ 13926.875	25	0.25	0.2630	0.000643
13926.875÷ 13931.25	18	0.18	0.1456	0.008127
13931.25÷ 13935.625	3	0.03	0.0474	0.006387
13935.625÷ 13940	1	0.01	0.0090	0.000111

According to Table 4, we calculated the value χ^2 according to Romanovsky's conformity standard as

$$\chi^2 = n.\sum_{i=1}^{8}\frac{(h_i - p_i)^2}{p_i} = 5.753454$$

On the other hand, the degree of freedom number of this conformity standard is $r = k-(s+1) = 8-(2+1) = 5$ (here $k=8$; $s=1$ because choosing a normal distribution has two parameters). From the table in reference [5, 6], we obtained the evaluation criteria with $\chi^2 = 5.753454$ and $r=5$ is $p(\chi^2, r) \approx 0.7 > 0.1$. This means that hypothesis about the piston outer diameter post-manufacture according to the normal distribution is appropriate.

Figure 4 and Figure 5 present the probability density and cumulative distribution of piston outer diameter and cylinder inner diameter.

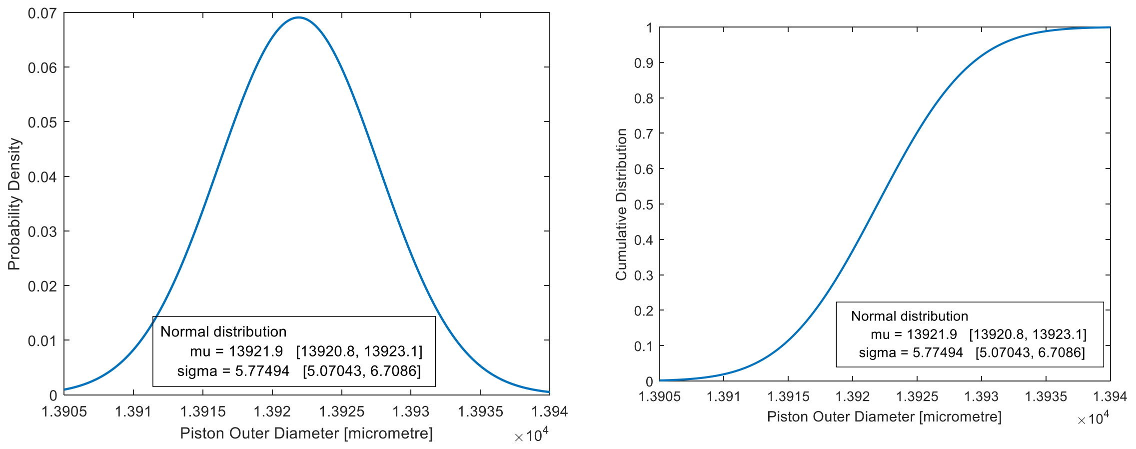

Figure 4. Probability density and cumulative distribution of piston outer diameter.

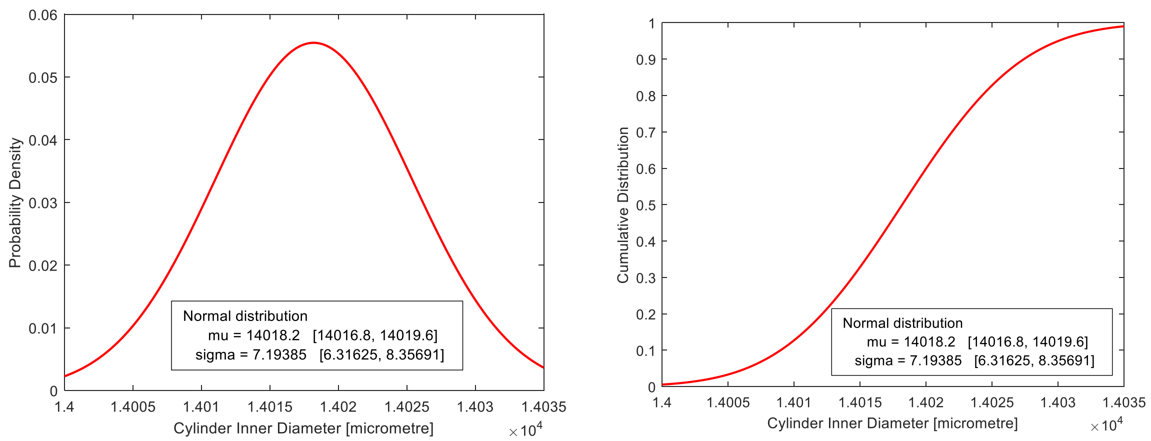

Figure 5. Probability density and cumulative distribution of cylinder inner diameter.

According to the probability, we found that:

- For piston outside diameter: there are 68.2 % pistons in the range [13.916 ÷ 13.928] mm, and 27.2 % pistons in the ranges [13.910 ÷ 13,916] mm and [13.928 ÷ 13,933] mm, (Figure 6). The mean diameter is 13.922 mm.

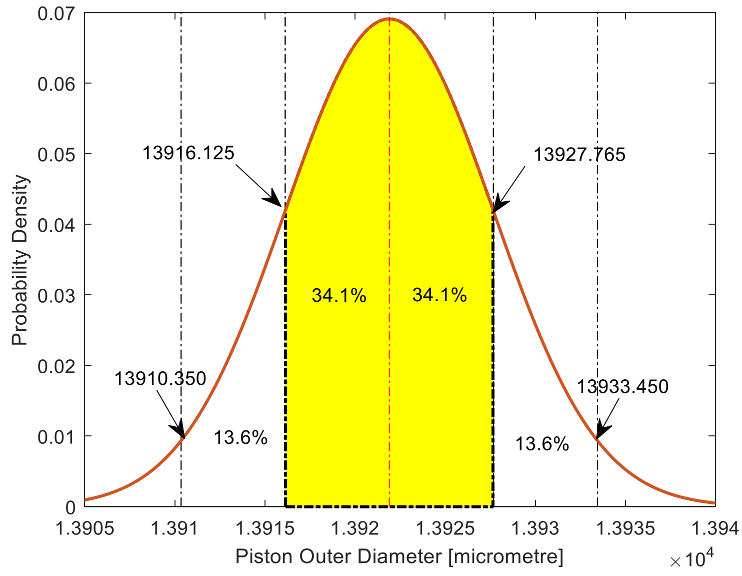

Figure 6. Probability density of piston outer diameter.

- For cylinder inner diameter: there are 68.2% cylinders in the range [14.011 ÷ 14.025], and 27.2 % cylinders in the ranges [14.004 ÷ 14.011] and [14.025 ÷ 14.033], (see Figure 7).

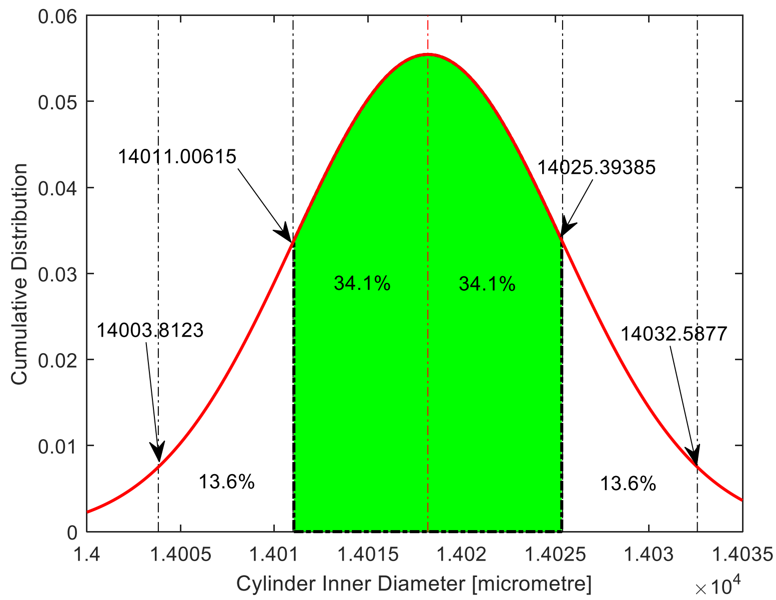

Figure 7. Probability density of cylinder inner diameter.

3. EFFECT OF DIAMETERS OF THE CYLINDER AND THE PISTON POST-MANUFACTURE ON THE OPERATION OF THE AUTOMATIC SYSTEM FOR GAS-OPERATED AUTOMATIC RIFLES

The influence of the diameters of the cylinder and the piston post-manufacture on the automatic system operation is expressed through the clearance between the piston and the cylinder and the diameter piston. The studied object is the automatic system of a 7.62 mm AKM-1 rifle. The dynamic model of the gas-operated automatic system with the fixed receiver is presented in reference [7, 8], and it is shown in Figure 8.

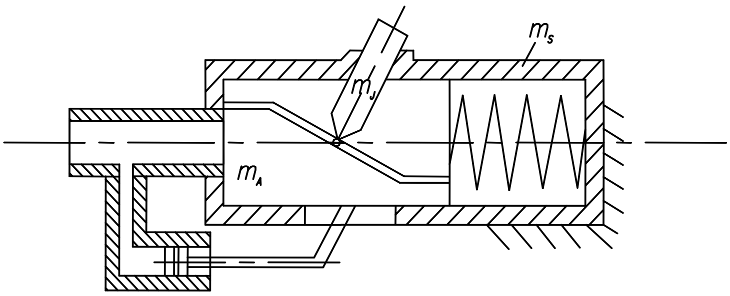

Figure 8. The dynamic model of the gas-operated automatic system with the fixed receiver.

The dynamic of the gas-operated automatic system is a combination of interior ballistic, thermodynamics of gas cylinder, and the motion of slide parts. The system equation of internal ballistics has been studied in references [7, 9] as

$$\begin{cases} \dfrac{dv}{dt} = \xi_1 \xi_3 \dfrac{p.S}{\varphi.m} \\ \dfrac{\mathrm{dl}}{\mathrm{dt}} = \xi_1 \xi_3 . v \\ \dfrac{\mathrm{dz}}{\mathrm{dt}} = \xi_2 \dfrac{p}{I_k} \\ \dfrac{\mathrm{d}\omega_c}{dt} = \xi_2 \chi . \omega_t \left(1 + 2\lambda z\right) \dfrac{p}{I_k} - \xi_b G_b - \left(1 - \xi_3\right) G_d \\ \dfrac{dw}{dt} = \xi_2 \dfrac{1 - \alpha\delta}{\delta} \chi . \omega_t \left(1 + 2\lambda z\right) \dfrac{p}{I_k} + \xi_3 s v \\ \dfrac{dp}{dt} = \dfrac{1}{w} \left\{ \left[\xi_2 \dfrac{p \chi . \omega_t}{I_k} \left(f - Kp \dfrac{1 - \alpha\delta}{\delta} \right) \left(1 + 2\lambda z\right) - KpSV \xi_3 \right] - K_{\mathrm{p}} \left[\xi_b G_b + \left(1 - \xi_3\right) G_d \right] - K_{\mathrm{t}} p \right\} \end{cases} \tag{3}$$

where $K_t = \dfrac{\left(k-1\right) A v_1 \sigma_T \left(F_k + \pi . d . l\right)}{R}$ - Heat loss function; F_k - Initial surface area of the gas chamber; $v_1 = 1 - \dfrac{T_{tb}}{T^0}$ with T_{tb} - Temperature of the inner surface of the barrel; $T^0 = \dfrac{P.w}{\omega_c . R}$ - Temperature of gases; $\mathrm{K_p} = \dfrac{\mathrm{k.P.w}}{\omega_\mathrm{T}}$ - Gas flow function; k - Multivariable index; $\mathrm{w} = \mathrm{w}_0 + S.l$

- Volume of space behind the bottom of the projectile; G_b - the flow of gas into the gas cylinder; G_d - the flow of gas through the muzzle barrel and

$$\begin{cases} G_b = \mu_\phi . S_\phi . \sqrt{\dfrac{p.\omega_c}{w}} \ . \left[\xi_4 A_1 + \left(1 - \xi_4\right) A_2 . A_2(\beta) \right] \\ G_d = \mu . S . \sqrt{\dfrac{p.\omega_c}{w}} \ . \left[\xi_d A_1 + \left(1 - \xi_d\right) A_2 . A_2(\beta) \right] \end{cases} \tag{4}$$

with $A_1 = \sqrt{gk\left(\dfrac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$ - Loss coefficient; $A_2(\beta) = \sqrt{\beta^{\frac{2}{k}} - \beta^{\frac{k+1}{k}}}$ - Loss function; $\beta = \dfrac{p_1}{p_2}$ with p_1, p_2 - The pressure in the gas cylinder where gas flows in and out; μ, μ_ϕ - flow loss coefficients when gas flow through the muzzle barrel and flows in the gas port; $\mu = 0.95, \mu_\phi = 0.3 \div 0.8$ for the 7.62 mm AKM-1.

The system equation thermodynamics in the gas cylinder has been studied in reference [9] as

$$\begin{cases} \dfrac{d\omega_b}{dt} = \xi_i \left(G_b - G_{bk} \right) \\ \dfrac{dw_b}{dt} = \xi_i \left(\dot{x} . S_b \right) \\ \dfrac{dp_b}{dt} = \dfrac{1}{w_b} \left(k.R.T.G_b - k.R.T_b - k.p_b.w_b \right) \xi_i \end{cases} \tag{5}$$

where ω_b - The weight of the gas flows into the cylinder; w_b - The volume of gas in the cylinder; S_b - Cross-sectional area of the piston; p_b - Pressure in the cylinder; $\dot{x}$ - Velocity of slide part; T_b - Temperature in the cylinder; $G_{bk} = \mu_k . S_\Delta . A_1 . \sqrt{\dfrac{P_b . \omega_b}{w_b}}$ - Flow of gas through the clearance between the piston and the cylinder; S_Δ - sectional area of the clearance between the piston and the cylinder; $\mu_k = 0.3 \div 0.5$ - flow loss coefficient.

The governing equation of the slide parts motion can be expressed as

$$\left(M_A + \sum_{i=1}^{n} \frac{K_i^2}{\eta_i} m_i \right) \frac{dV_A}{dt} + \sum_{i=1}^{n} \frac{K_i}{\eta_i} m_i \ V_A^2 \frac{dK_i}{dx} = F_A - \sum_{i=1}^{n} \frac{K_i}{\eta_i} F_i \ . \tag{6}$$

The equation is abbreviated as

$$M'_A \ddot{x} + \dot{x}^2 M_{qt} = P'_A \ . \tag{7}$$

where $M'_A = M_A + \sum_{i=1}^{n} \dfrac{K_i^2}{\eta_i} m_i$ - the compact mass of slide part motion; $M_{qt} = \sum_{i=1}^{n} \dfrac{K_i}{\eta_i} m_i \dfrac{dK_i}{dx}$ - the added inertial mass of working parts m_i; $P'_A = F_A - \sum_{i=1}^{n} \dfrac{K_i}{\eta_i} F_i$ - the compact force acting on the slide part motion.

In order to evaluate the influence of diameters of the cylinder and the piston post-manufacture on the operation of the automatic system, we studied 5 cases as shown in Table 5.

Table 5. Investigated cases.

No.	Cylinder inner diameter d_v (mm)	Piston outer diameter d_p (mm)	Clearance (2Δ - Figure 1) (mm)	Explain
1	14.000	13.905	0.095	d_v – min; d_p – min
2	14.000	13.940	0.06	d_v – min; d_p – max
3	14.035	13.905	0.13	d_v – max; d_p - min
4	14.035	13.940	0.095	d_v – max; d_p - max
5	14.018	13.922	0.096	Mean diameter

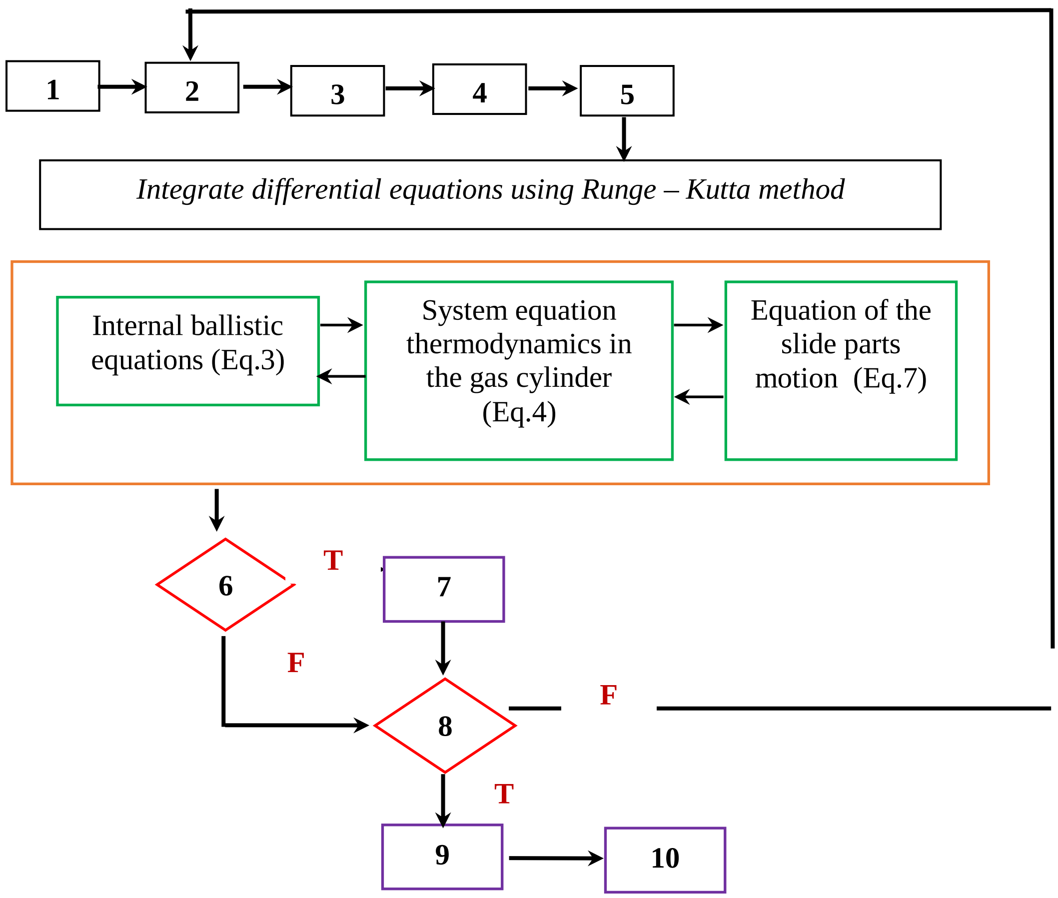

Figure 9. The algorithm diagram to solve the dynamic model.

1. Input data; 2. Forces are acting on the slide parts; 3. Determine the value of the resistance force; 4. Determine the value of K_i, η_i; 5. Determine the value of ξ_i; 6. Consider the condition of the collision; 7. Determination of velocity change due to collision; 8. Analysis of the end condition; 9. Results; 10. Stop.

The software program used to solve the dynamic model was the Matlab environment with the algorithm diagram, as shown in Figure 9. Selected results are presented in Figure 10 and Figure 11.

The calculation results show that:

- When the clearance between the piston and the cylinder decreases, the pressure curve in the cylinder gas rise (see Figure 10). The pressure is biggest (23.46 MPa) when the cylinder inner diameter is minimum, and the piston outer diameter is maximum in case 2. Moreover, vice versa, the pressure is smallest (22.5 MPa) when the cylinder inner diameter is maximum and the piston outer diameter is minimum in case 3. So the differential pressure in the cylinder gas of the 7.62 mm AKM-1 rifle post-manufacture is 0.96 MPa.

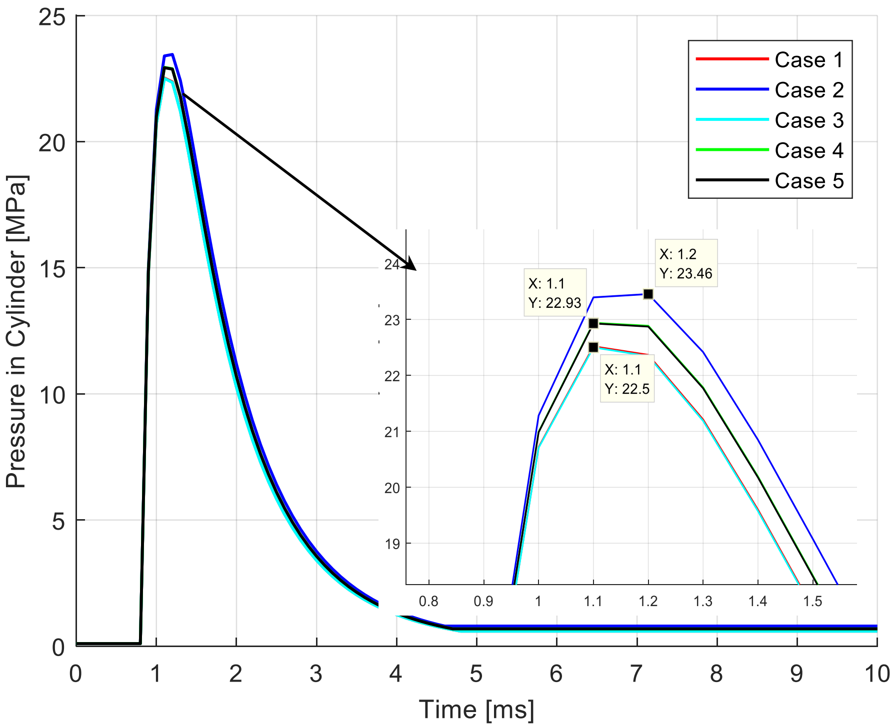

Figure 10. Pressure in the cylinder gas vs. time.

- According to the pressure changes in the cylinder, the kinetic characters of the bolt-carrier also change. This means that when the clearance between the piston and the cylinder decreases, the velocity of the bolt-carrier rises (Figure 11). The maximum velocity is 7.212 m/s in case 2, and the minimum is 6.684 m/s in case 3. Corresponding to it is a decrease of bolt-carrier at the rear position from 3.188 m/s to 2.395 m/s. Finally, the motion cycle time of the bolt-carrier also decreases from 101.5 ms to 92.2 ms. So the cyclic rate of fire of the 7.62 mm AKM-1 rifle post-manufacture is 591 ÷ 651 rds/min [10]. These values are completely consistent with the current technical conditions for acceptance of the 7.62 mm AKM-1 rifle post-manufacture [10].

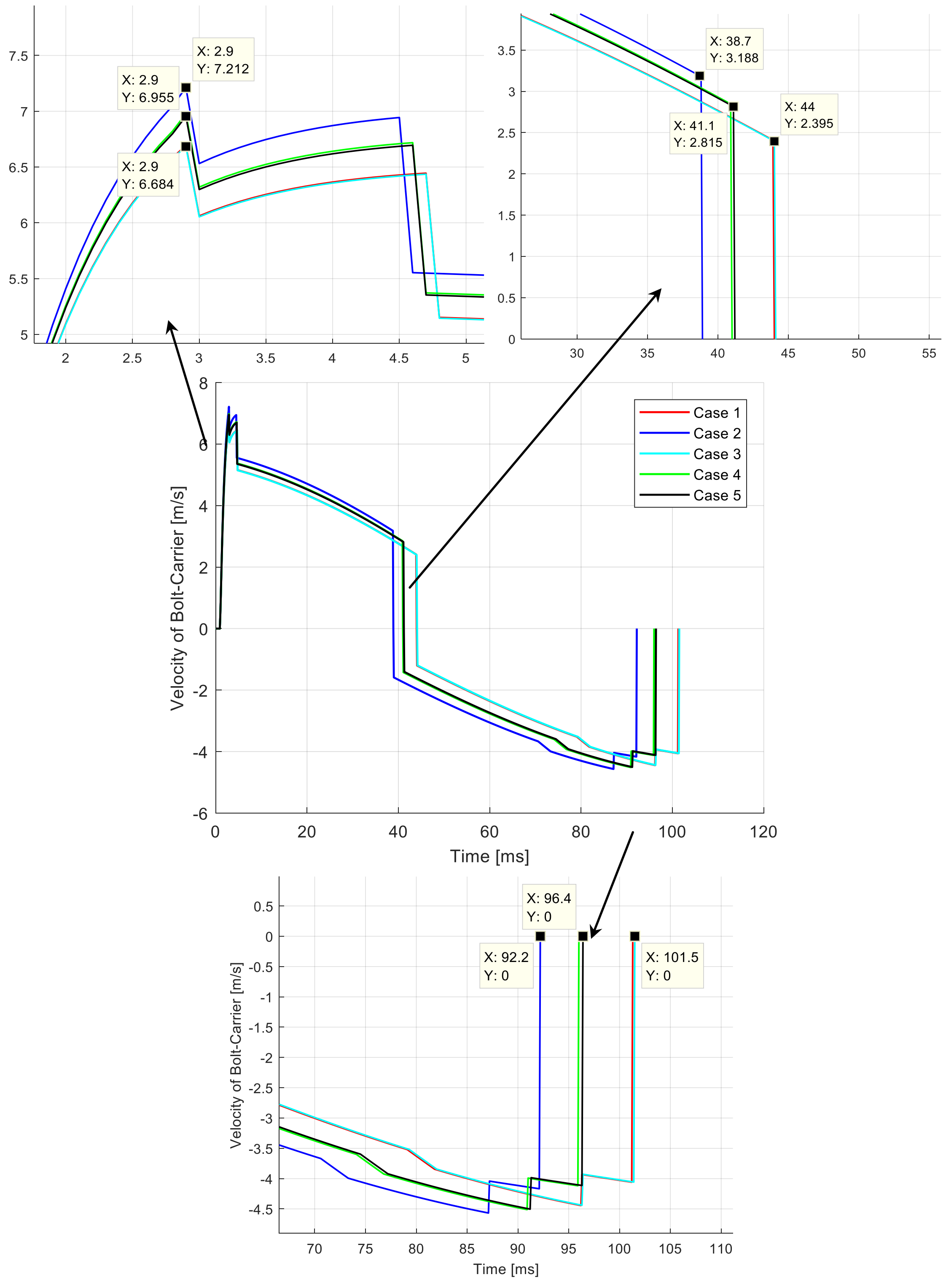

Figure 11. The velocity of bolt-carrier vs. time.

4. CONCLUSIONS

The paper has investigated the distribution and effect of diameters of the cylinder and the piston post-manufacture on the operation of gas-operated automatic rifles, with the study object being 7.62 mm AKM-1 rifles. The findings of this study suggest that:

- The cylinder inner diameter and the piston outer diameter post-manufacture of 7.62 mm AKM-1 rifles follow the normal distribution. Moreover, we can predict the distribution of dimensions of guns post-manufacture by the method used in the article.
- The results of analysis of dynamics of the automatic system in 5 cases with the maximum, minimum, and most probable are completely consistent with the current technical conditions for gun acceptance post-manufacture.
- The study method in this paper can be used as a powerful tool for establishing technical conditions for new gun acceptance post-manufacture.

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