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PRESSURE DISTRIBUTION IN THE SPACE BEHIND A PROJECTILE

Reviewer: Bohumil PLÍHAL

A b s t r a c t :

This article deals with modelling of pressure distribution of propellant gases in space behind the projectile of ordinary ballistic system. The number of existing models is analyzed and confronted with results of unique experimental firings carried out on the high performance ballistics system of calibre of 30 mm.

1. Introduction

During a movement of a projectile inside the barrel is created the pressure gradient between barrel breech and shot base due to the difference in velocities of propellant gases at the breech and the shot base, Figure 1. This pressure gradient belongs among factors that significantly affect interior ballistic calculations. The pressure gradient is usually characterised by the ratio of the breech pressure p_d and the shot base pressure p_s.

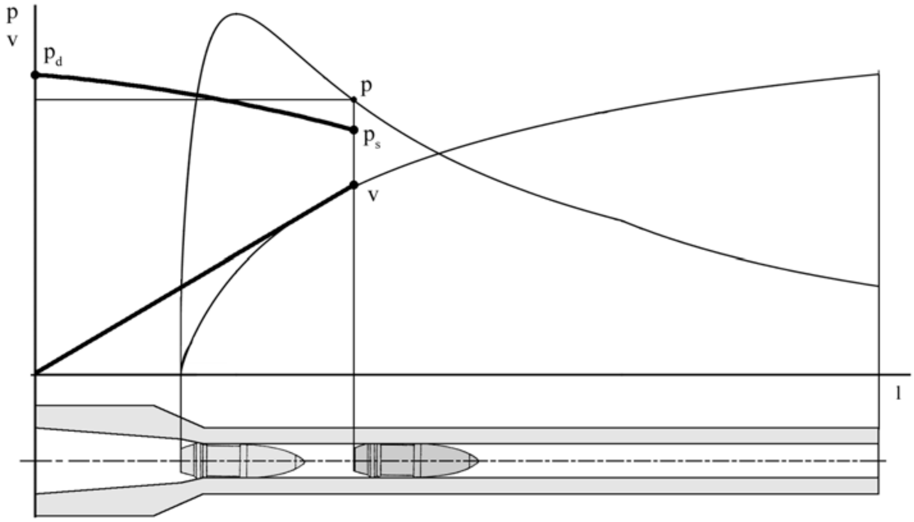

Figure 1 Pressure gradient in the space behind a projectile
p ... ballistic pressure, *v* ... velocity of projectile, *l* … projectile's trajectory

The literature [1], [7] contains number of models describing the pressure gradient but without any comparison with experimental results. Most of the models are relatively old and were created for ballistic systems of lower performance, e.g. howitzers. There is not any study analysing the suitability of these models for modern medium calibre and high performance ballistic systems that still satisfy the condition $\omega / m_q < 1$.

2. Models of pressure distribution

From above mentioned literature four the most widespread models describing the pressure gradient in the space behind a projectile were chosen and were marked for needs of this article as Model 1 – 4. The fifth pressure distribution model is used at the interior ballistic model described at [3] and was marked as model STANAG 4367.

Generally, it can be said, that basic element of all analysed models of pressure gradient is the ratio $\dfrac{\omega}{2 \cdot m_q}$,

where:

ω … mass of propellant charge,

m_q … mass of the projectile.

2.1. Model 1

This model is determined for ballistic systems with a cylindrical cartridge chamber of the same area of cross-section as area of cross-section of barrel, Figure 2.

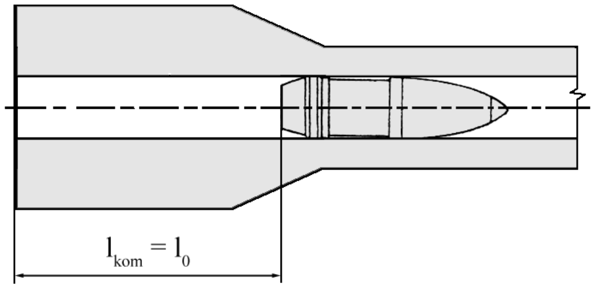

Figure 2 Schema of cylindrical cartridge chamber ($l_{kom} = l_0$)
l_{kom} … length of cartridge chamber, l_0 … length of initial combustion volume

At this model is the ratio of breech pressure to the shot base pressure expressed as

$$\frac{p_d}{p_s} = 1 + \frac{\omega}{2 \cdot \varphi_1 \cdot m_q}, \tag{1}$$

where:

p_d ... breech pressure,

p_s ... shot base pressure,

ω ... mass of propellant charge,

m_q ... mass of projectile,

φ_1 ... losses coefficient (usually between 1.02 (howitzers and cannon) and 1.1 (small arms 1.05 - 1.1), [7], [8]).

At this model the ratio p_d / p_s strongly depends only on ratio ω / m_q and remains constant during the projectile's movement inside the barrel, i.e. the ratio is independent of the projectile's trajectory. The dependency for common extent of values ω / m_q is shown at Figure 3.

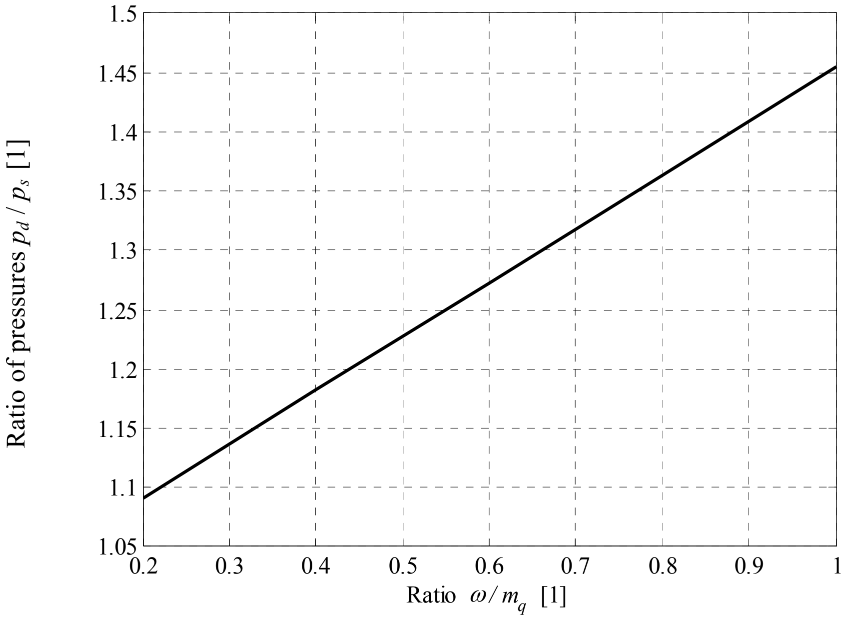

Figure 3 Dependency of p_d / p_s on ratio ω / m_q

$\varphi_1 = 1.1$

From the Figure 3 is clearly seen that according to the Model 1 is the pressure ratio p_d / p_s directly proportional to the ratio ω / m_q.

2.2. Model 2

A real cartridge chamber has usually bigger diameter than the diameter of the barrel, Figure 4. This model is based on the Model 1 and extended by an effect of cartridge chamber shape. The effect of the cartridge chamber shape is described by the coefficient of cartridge chamber shape $\chi = \frac{l_0}{l_{kom}}$.

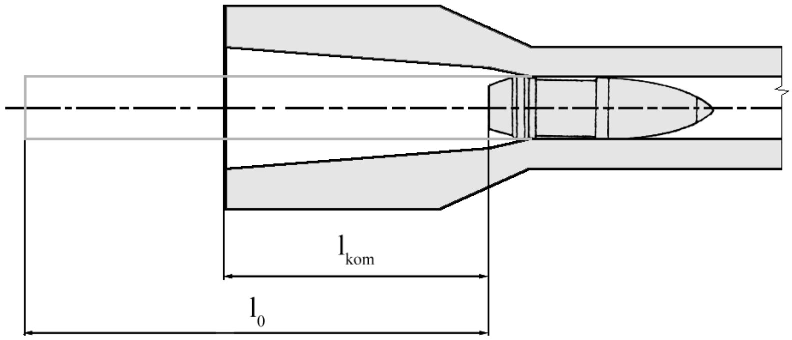

Figure 4 Schema of real cartridge chamber ($l_{kom} \neq l_0$)

The ratio of breech pressure p_d to the shot base pressure p_s is, in this model, described by following empirical relation:

$$\frac{p_d}{p_s} = \left(1 + \frac{\omega}{2 \cdot \varphi_1 \cdot m_q}\right) \cdot \left(\frac{1}{\chi}\right)^k, \tag{2}$$

where:

χ ... coefficient of cartridge chamber shape,

k ... exponent (recommended value 0.3, [1]).

For calculation of exemplary courses of p_d / p_s were chosen typical extent of ratios ω / m_q from 0.2 to 1.0, exponent k = 0.3 according to recommendations from literature, and coefficient φ_1 = 1.1. The obtained dependencies of p_d / p_s are shown at Figure 5.

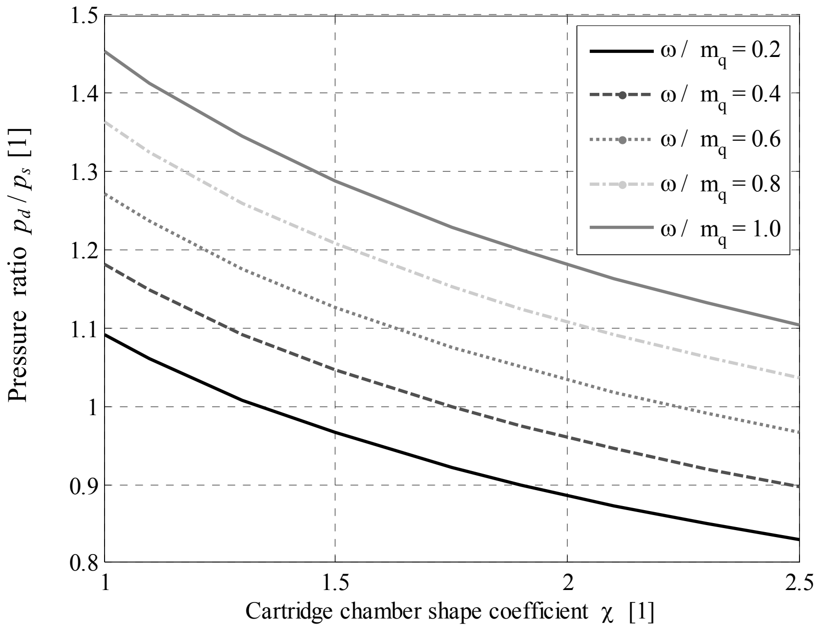

Figure 5 Dependency of p_d / p_s on cartridge chamber shape coefficient χ

$\varphi_1 = 1.1$, $k = 0.3$

The ratio p_d / p_s is again independent of the projectile's trajectory and remains constant during the projectile's movement inside the barrel. Generally, the ratio p_d / p_s decreases with increasing cartridge chamber shape coefficient χ and with decreasing ratio ω / m_q.

Further the figure shows that there are, according to this model, certain combinations of cartridge chamber shapes coefficients χ and ratios ω / m_q that gives p_d / p_s smaller than 1; in other words the breech pressure would be lower than the shot base one. This fact is, in case of classical ballistic systems satisfying the condition $\omega / m_q < 1$, unexplainable.

2.3. Model 3

The Model 3 is also based on the Model 1. This time is the Model 1 extended not only by the effect of the shape of cartridge case chamber χ but also by the effect of increasing volume of the space behind the projectile expressed by the projectile's trajectory l.

$$\frac{p_d}{p_s} = 1 + \frac{\omega}{2 \cdot \varphi_1 \cdot m_q} \cdot \left(1 - \frac{\chi - 1}{\chi \cdot \left(1 + \frac{s \cdot l}{c_0} \right)^3} \right), \quad (3)$$

where:

s ... cross-sectional area of barrel,

c_0 ... initial volume of cartridge chamber.

The ratio p_d / p_s was calculated again for typical values and is shown at Figure 6. From the figure is clearly seen that p_d / p_s increases with the trajectory of the projectile and also with ratio ω / m_q. The increase of p_d / p_s is the steepest at the beginning of projectile's movement and later becomes nearly constant.

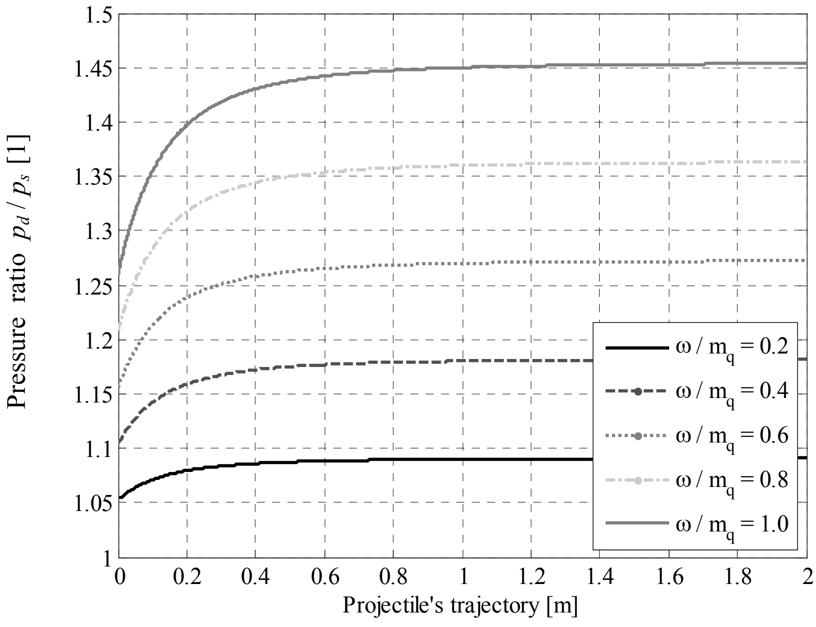

Figure 6 Dependency of p_d / p_s on projectile's trajectory

$\varphi_1 = 1.1$, $c_0 / s = 0.4$, $\chi = 1.75$

2.4. Model 4

As a last of the most used models of the pressure gradient in the space behind the projectile that takes into account except ω and m_q, also χ and relative projectile's trajectory Λ. The ratio p_d / p_s is given by following relation

$$\frac{p_d}{p_s} = 1 + \frac{\omega}{2 \cdot \varphi_1 \cdot m_q} \cdot \left(1 - \frac{1 - \frac{1}{\chi^2}}{(1+\Lambda)^2} \right), \tag{4}$$

where:

$$\Lambda = \frac{s \cdot l}{c_0}.$$

For calculation was again chosen the typical extent of ratios ω / m_q from 0.2 to 1.0. The obtained dependencies are shown at Figure 7. The figure shows that p_d / p_s increases with the trajectory of the projectile and also with ratio ω / m_q. The increase of p_d / p_s is again the steepest at the beginning of projectile's movement.

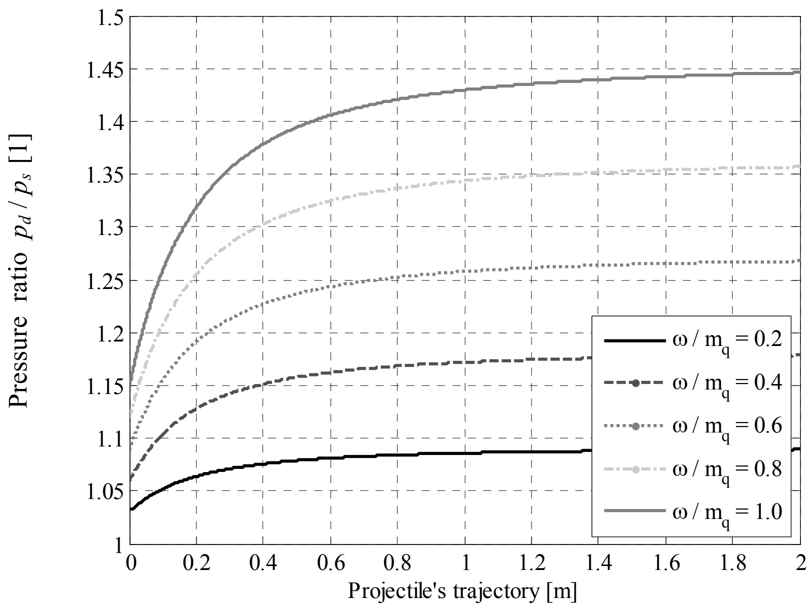

Figure 7 Dependency of p_d / p_s on projectile's trajectory
$\varphi_1 = 1.1$, $c_0 / s = 0.4$, $\chi = 1.75$

2.5. Model STANAG 4367

In the Model STANAG 4367 that is a part of the interior ballistic model described at standard STANAG 4367 is the ratio p_d / p_s given by the following relation

$$\frac{p_d}{p_s} = 1 + \frac{\omega}{2 \cdot m_q} \cdot \left(1 - \frac{p_R}{p_s} - \frac{p_g}{p_s}\right), \tag{5}$$

where:

p_R ... resistance pressure against projectile's motion,

p_g ... pressure of gases ahead of projectile.

It can be seen that the ratio p_d / p_s depends not only on ω and m_q but also on ratios p_R / p_s and p_g / p_s. All variables, with exception of ω and m_q, are time dependent, and so the ratio p_d / p_s is not constant during projectile's movement inside the barrel. Typical course of ratio p_d / p_s on projectile's trajectory is shown at Figure 8.

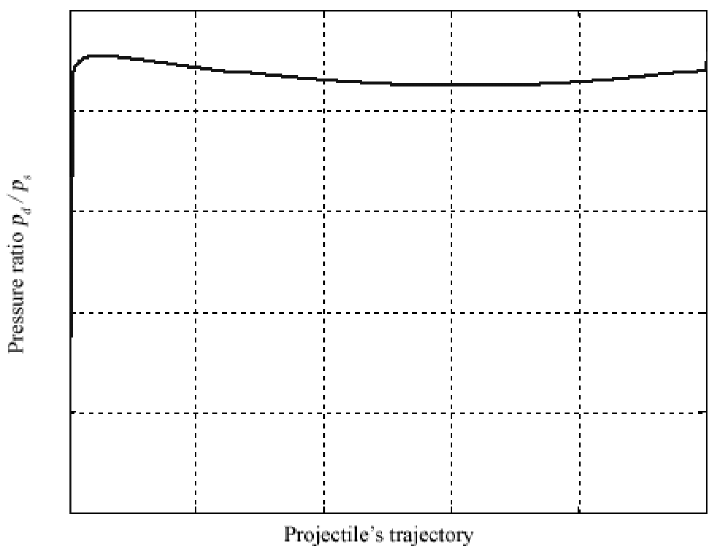

Figure 8 Dependency of p_d / p_s on projectile's trajectory

All previously analyzed models were used for calculation of ratios p_d / p_s for a ballistic systems of calibre of 30 mm that was later also used for experiments. Its ballistic characteristics were $\omega = 0.185$, $m_q = 0.389$ kg, $\chi = 1.9$, $\varphi_1 = 1.03$, $c_0 = 2.319\text{e-}4$ m^3,

s = 7.364e-4 m^2. Obtained theoretical results are summarized at Table 1. Distances of individual pressure gauges from back of barrel are shown at Figure 9.

Table 1

Results of calculations of p_d / p_s from individual models

Gauge No.	2	3	4	5	6
Model 1	1.23	1.23	1.23	1.23	1.23
Model 2	1.01	1.01	1.01	1.01	1.01
Model 3	1.16	1.22	1.23	1.23	1.23
Model 4	1.11	1.19	1.22	1.22	1.23
Model STANAG 4367	1.22	1.22	1.21	1.21	1.22

3. Experiments

For the validation of all previously mentioned models of the pressure distribution at the space behind the projectile it is necessary to know the breech pressure p_d and the shot base p_s. The experiment was focused on the measurement of the pressure of propellant gases at the breech and at the base of the projectile.

The measurement of the shot base pressure was realized by means of five piezoelectric pressure gauges placed along the barrel, Figure 9. The shot base pressure was read when the projectile passed the individual pressure gauges.

For the experiment the ballistic testing weapon of caliber of 30 mm based on anti-aircraft gun 30 mm PLDvK M 53 was used. For the test firings was used practice ammunition 30 mm JNhSv, v_0 = 1000 m.s^{-1}. The schema of used ballistic barrel with positions of piezoelectric pressure gauges is shown at Figure 9.

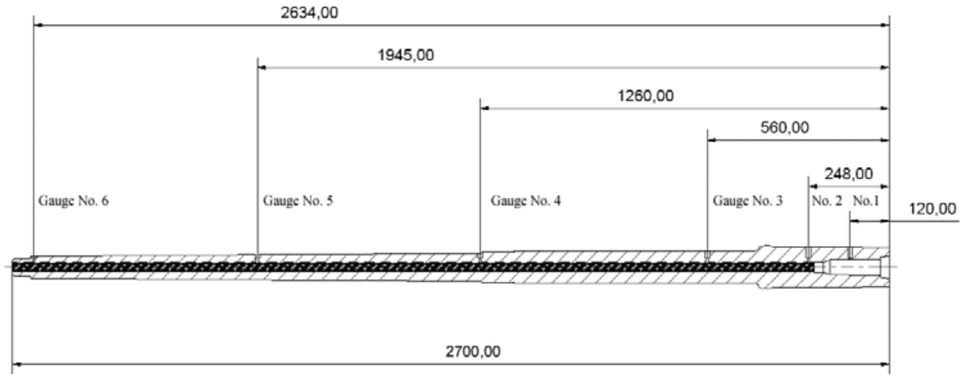

Figure 9 Schema of ballistic barrel with positions of pressure gauges

Example of measured pressures on all pressure gauges is shown at Figure 10.

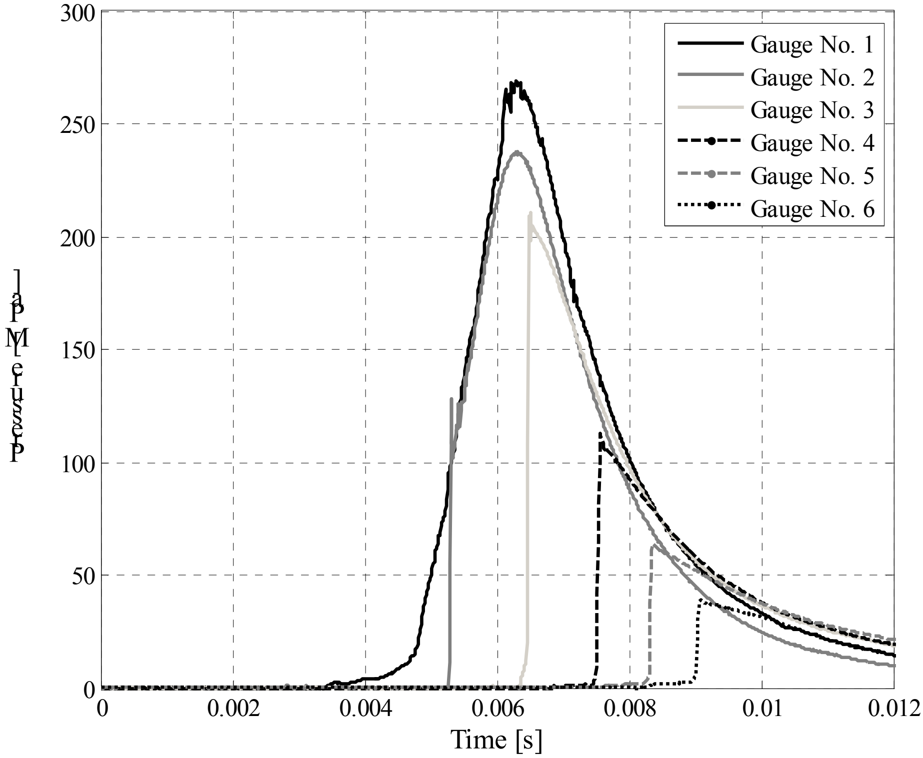

Figure 10 Example of measured pressures

4. Results of experiment and their analysis

From obtained experimental data were determined pressures at individual gauges (Gauges No. 2 - 6) at instant of projectile's arrival p_s and their corresponding breech pressures p_d (Gauge No. 1). The evaluated values of both pressures together with corresponding pressure ratios p_d / p_s are summarized at Table 2.

Table 2

Results of experimental firings

Gauge No.	2	3	4	5	6
p_d [MPa]	100.45	246.77	130.77	78.27	51.18
p_s [MPa]	100.45	201.68	108.41	63.55	38.09
p_d/ p_s [1]	1.00	1.22	1.21	1.23	1.34

Calculated and experimentally obtained ratios p_d / p_s are compared at Figure 11. At experimentally obtained ratios p_d / p_s are also shown their corresponding standard deviations.

From comparison of results of calculations and experimentally obtained p_d / p_s follows that the results of calculations are in good agreement with experiment data, especially in the middle part of the barrel. The only exception is the Model 2 whose results do not agree neither with results of experiment nor with results of other models. This disagreement is caused by inappropriate value of the exponent k. From the comparison can be further seen that at the beginning of projectile's motion and near the muzzle is the difference between results of calculations and experiments more significant.

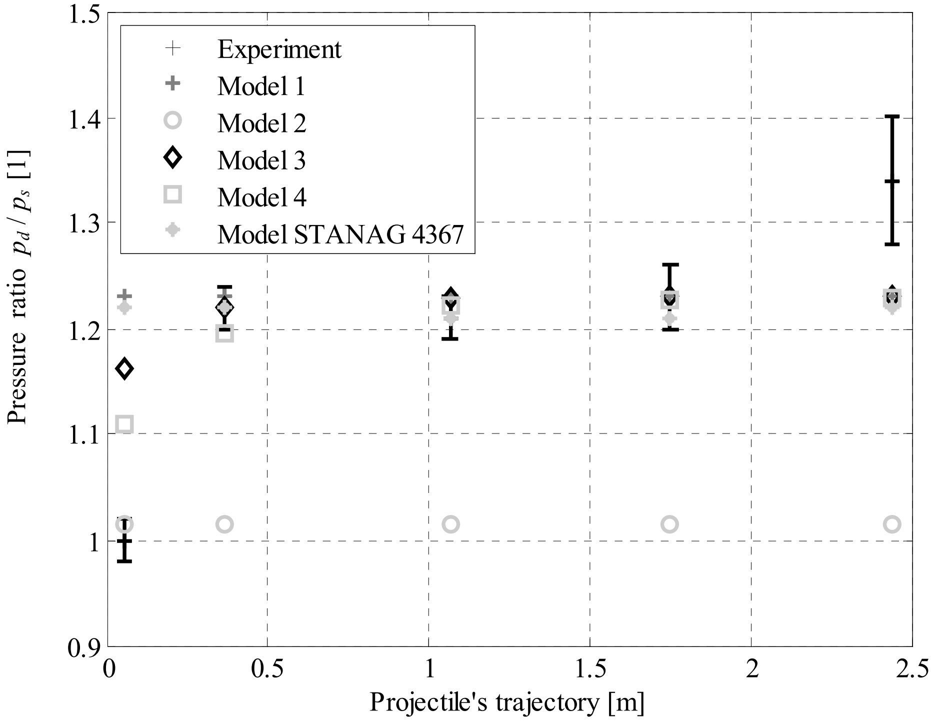

Figure 11 Comparison of experimental and calculated p_d / p_s

5. Conclusions

The bigger difference between measured and calculated ratios p_d / p_s near the muzzle of the barrel can be explained by the leak of propellant gases between barrel wall and driving band that is at this stage of projectile's movement worn. Barrel wear usually also grows towards the muzzle of barrel.

Common disadvantage of all the analysed models is the fact that none of them takes into account the leakage of propellant gases. In other words, due to wear of the driving band is changed the contact pressure between the driving band and the barrel wall.

The Model 2 requires more suitable value of the exponent k to get into better agreement with experimental results.

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