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Analysis of the Released Plug Assembly Motion

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Abstract:

The article is focussed on the quasi-dynamic analysis of the released plug assembly motion due to the acting fluid force. The request for this analysis is connected with the pressure testing of high-pressure valves. There exists a real danger of the failure of the plug clamping system causing the plug assembly to fly off. The hydrodynamic model of the problem describes the plug motion in three phases of fluid flow and was solved using the MATLAB code. Presented analysis enables us to understand how the plug assembly mass and dimensions influence the plug assembly fly off motion. Further, we can understand the effect of the test pressure and the system inner volume. This analysis provides the input data applicable for the design of a restraint system, which is part of the testing box for high-pressure valves.

Keywords:

Fluid dynamics, high-pressure equipment, fluid discharge, fly off

1. Introduction

Any pressurized system represents a potential danger due to the high pressure under which it operates. High pressure systems are frequently the source of serious accidents. Even non-dangerous gases and liquids, such as air and water, may become hazardous in the event of an accident involving high-pressure equipment. These accidents may cause death, serious bodily injury or substantial property damage. Accidents involving high-pressure equipment cover mainly:

- Failures of pressure vessels or boilers
- Hydraulic hose or pipe whip accidents
- Failures of high-pressure hydraulic fittings or suddenly released parts
- Fluid injection injury

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In order to investigate and prevent accidents potentially occurring in pressurized equipment, it is useful to apply suitable mathematical model describing the processes and fluid forces caused by discharge of fluid through a failure opening area. Seeing that, the detailed knowledge of velocity distribution is not substantial for the mentioned fluid forces determination; however, the one-dimensional model of fluid flow appears to be acceptable. With regard to failure opening time, the results of quasi-dynamic analysis of the interaction with the surrounding can be considered as a conservative solution [1].

The fluid force acting on the fluid system (see Fig. 1) is function of time and space. This force depends on the fluid thermodynamic state in the control volume and flow plane area in and out of the control volume. The generalized equation [1], which describes the fluid force acting on the part of fluid system, is given in the form

$$F = -\int_{c.v.} \frac{\mathrm{d}(\rho_\mathrm{w}\, c)}{\mathrm{d}\,\tau}\mathrm{d}V - \rho_\mathrm{w}\, c^2 A - pA + p_\mathrm{a} A\,. \tag{1}$$

Here F is the fluid force, $c.v.$ is the control volume, ρ_w is the fluid density, c is the control volume fluid velocity, A is the control volume discharge plane area, p is the fluid pressure at opening plane area, p_a is the ambient pressure.

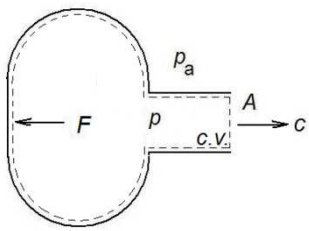

Fig. 1 Schematic of fluid system

The first term of Eq. (1) is the acceleration term, which can be considered as small. When steady state flow conditions are reached, this term due to fluid acceleration vanishes.

Authors of the article have realized several cases of the mathematical simulation of the processes involving pressurized equipment, e.g.:

- Quasi-dynamic analysis of the primary circuit head motion released by breaking its bolts for design of an absorbing ring [2]
- Solution of two-phase fluid discharge from a steam generator into the surroundings through a throttling nozzle [3]
- Analysis of processes and fluid forces connected with a pressure vessel rupture [4]
- Fluid thrust forces solution for a pipe whip restraint analysis [3]

The request for the current analysis is connected with the pressure testing of high-pressure valves. For these tests, all openings of the tested valves are sealed with plugs, which are attached by flanges and fasten by bolts (Fig. 2). The tested valves are filled with water and then pressured up to 140 MPa. During the filling process, some amount of residual air may remain in a system, up to 15 % of the system inner volume at barometric conditions.

There exists a real danger of the failure of the plug's clamping system causing the plug assembly to fly off. This failure causes opening of the pressurised system and can cause a person to be struck by released flying parts or pressurized fluid once the pressure is released.

The topic of this article is focussed on the detailed analysis of the released plug assembly motion due to acting the fluid force. This analysis provides the input data applicable for the design of a restraint system, which is a part of the testing box for high-pressure valves (design of protection walls, their fixation to the ground, stability at impact, etc.). The following article states a procedure for determining the metal protection wall limit thickness of the restraint system (safety barrier system).

2. Bases and Assumptions of Solution

Schematic of the sealing plug assembly, which is attached on the tested valve corpus, is shown in Fig. 2. The plug closing the valve opening is sealed by the O-ring, which is located at the plug's cylindrical shaft.

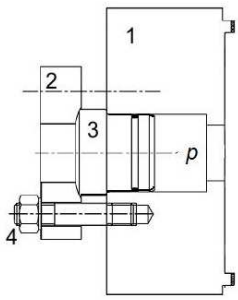

Fig. 2 Schematic of the sealing plug assembly: 1 – valve corpus, 2 – flange, 3 – plug, 4 – fasting bolt, p – test pressure

Analysis of the released plug assembly motion has been performed for various sizes of tested valves and test pressures. Dimensions and other input data for the required analysis are given in Tab. 1.

Tab. 1 Input data of the released plug assembly motion analysis

Plug assembly option	1.a / 1.b / 1.c	2.a / 2.b / 2.c	3.a / 3.b / 3.c
Plug shaft diameter d [mm]	60	85	115
Plug shaft length x_L [mm]	52	52	170
Plug assembly mass m_{pl} [kg]	11.9	13.8	28.2
Test pressure p_0 [MPa]	140	80	100
Valve inner volume V_{w0} [L (litre)]	2 / 25 / 50	2 / 25 / 50	2 / 25 / 50
Residual air volume V_{air0} [L]	0.3 / 3.75 / 7.5	0.3 / 3.75 / 7.5	0.3 / 3.75 / 7.5

The quasi-dynamic analysis of the released sealing plug assembly free displacement is based on the following simplifications:

- Plug assembly is released suddenly (e.g. sudden break of all fastening bolts)
- The plug assembly moves as one body in the direction of valve opening axis
- Tests are carried out at the room temperature of 20 °C
- Influence of the mechanical friction and the aerodynamic drag are neglected during the plug assembly motion
- Valve structure deformations due to pressure changes are neglected
- Residual air remaining in a valve represents 15 % of the system inner volume at barometric conditions and this air pocket is located outside the opening
- Expansion of the air pocket due to the pressure release is described by an approximation polytropic process

3. Hydrodynamic Model of the Process

In the flows around or through bodies, the effects of the fluid force are determined by the Newton's Second Law, which also implies the law of conservation of momentum. We investigate the fluid forces and the rate of change of the linear momentum for the given flow around or through bodies by using a suitably chosen control volume bounded by the control surface. The advantage of applying the momentum principle is given by the fact that we can determine the force acting on body only from the knowledge of the fluid variables (velocity and pressure) on the control surface.

Acceleration of the released plug assembly is given by the acting of the fluid force F on the plug assembly of mass m_{pl} as

$$\frac{\mathrm{d}c_{\mathrm{pl}}}{\mathrm{d}\tau} = \frac{F}{m_{\mathrm{pl}}} \tag{2}$$

and the velocity of plug assembly displacement is

$$c_{\mathrm{pl}} = \frac{\mathrm{d}x_{\mathrm{pl}}}{\mathrm{d}\tau}\,, \tag{3}$$

where x_{pl} is the plug displacement.

As the system inner volume remains constant during the water discharge and the consequent pressure release, the change in water volume determines the change in air pocket volume within the examined system, thus

$$\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau} = -\frac{\mathrm{d}V_{\mathrm{air}}}{\mathrm{d}\tau}\,. \tag{4}$$

The change in water volume within the valve system is given by the change in water volume due to the rate of water discharge and due to the fluid compressibility, as

$$\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau} = -\left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}} + \left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{comp}}\,. \tag{5}$$

The change in water volume due to the fluid compressibility is characterized by the coefficient of water volume compressibility δ_{w} as

$$\left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{comp}} = -\frac{\mathrm{d}p}{\mathrm{d}\tau}\,\delta_{\mathrm{w}}\,V_{\mathrm{w}}\,, \tag{6}$$

where $\delta_w = 0.495\times10^{-9}$ Pa^{-1} and V_w is the instant volume of water within the valve system.

The change in air pocket volume, which is determined by the change in water volume (4), can also be expressed as the air pocket polytropic expansion by

$$\frac{\mathrm{d}V_{\mathrm{air}}}{\mathrm{d}\tau} = -\frac{1}{n\,k\,V_{\mathrm{air}}^{-n-1}}\frac{\mathrm{d}\,p}{\mathrm{d}\tau}\,. \tag{7}$$

This equation is given by the derivative of the equation of polytropic process in form

$$p\,V_{\mathrm{air}}^{n} = k\,. \tag{8}$$

Polytropic approximation of the air pocket expansion was performed for all given cases of the residual air volume (Tab. 1) by using the gas equation of state and applying the compressibility factor [5]. Example of such approximation of the air pocket polytropic expansion for residual air volume at barometric conditions 7.5 lifters is shown in Fig. 3, were the polytropic exponent n = 1.16 and the constant k = 180.

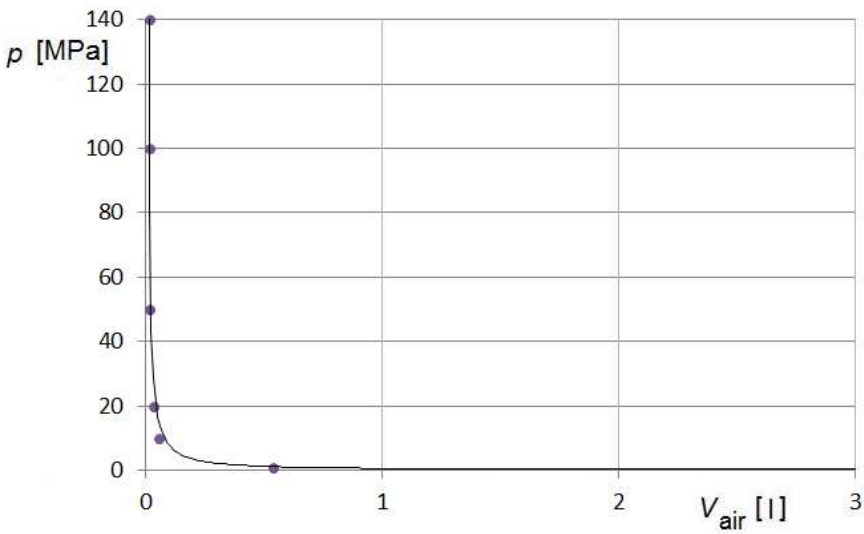

Fig. 3 Example of approximation of air pocket polytropic expansion

By introducing Eqs (4), (5) and (6) into Eq. (7) and by rearranging it, we can obtain the change in pressure of the fluid within the valve system in form

$$\frac{\mathrm{d}\,p}{\mathrm{d}\tau} = \frac{-\left(\dfrac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}}}{\dfrac{1}{n\,k\,V_{\mathrm{air}}^{-n-1}} + \delta_{\mathrm{w}}\,V_{\mathrm{w}}}\,. \tag{9}$$

The change in water volume due to the rate of water discharge is determined by the kind of discharging process, which varies according to the hydrodynamic model of the fluid flow. We can distinguish three phases of water discharge process during the plug displacement.

3.1. First Phase of the Plug Displacement

The first phase of the plug assembly motion represents the displacement of the plug shaft inside the valve opening, i.e. the displacement x_{pl} from 0 to x_L (see Fig. 4).

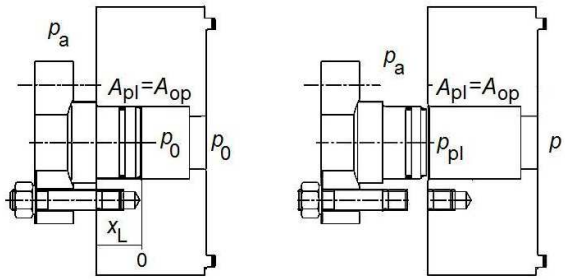

Fig. 4 The first phase of plug displacement

In this case the change in water volume within the valve system is given by the plug shaft displacement x_{pl}. Thus

$$\left(\frac{\mathrm{d}V_w}{\mathrm{d}\tau}\right)_{dis} = A_{pl}\frac{\mathrm{d}x_{pl}}{\mathrm{d}\tau} = \frac{\pi d^2}{4}\, c_{pl}\,. \tag{10}$$

The pressure force acting upon the plug shaft surface A_{pl} during the first phase of the plug displacement is given by

$$F = A_{pl}\left(p_{pl} - p_a\right) = \frac{\pi d^2}{4}\left(p - \frac{\rho_w c_{pl}^2}{2} - p_a\right), \tag{11}$$

where the pressure on the plug shaft surface p_{pl} is expressed by applying the Bernoulli equation [6].

3.2. Second Phase of the Plug Displacement

The second phase of the plug assembly motion represents the plug free displacement x_{pl} from x_L to $x_L + d/4$ (see Fig. 5). The end of this phase of plug motion, which is given by the displacement $x_{pl} = x_L + d/4$, is when the water discharge flow area is equal to the valve opening area, i.e. $A_{dis} = A_{op}$.

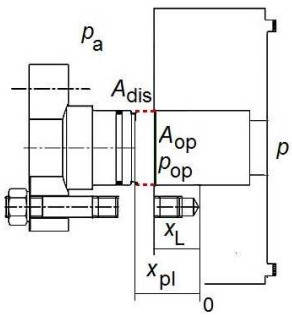

Fig. 5 The second phase of plug displacement

During this phase, the change in water volume within the valve system is given by the volumetric flow discharge through the flow area A_{dis} and by the velocity of plug motion. Thus

$$\left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}} = \mu A_{\mathrm{dis}}\sqrt{\frac{2(p-p_{\mathrm{a}})}{\rho_{\mathrm{w}}}} + A_{\mathrm{op}}\frac{\mathrm{d}x_{\mathrm{pl}}}{\mathrm{d}\tau} = \mu\pi d\left(x_{\mathrm{pl}} - x_{\mathrm{L}}\right)\sqrt{\frac{2(p-p_{\mathrm{a}})}{\rho_{\mathrm{w}}}} + \frac{\pi d^2}{4}c_{\mathrm{pl}}, \quad (12)$$

where the coefficient of water discharge $\mu = 0.6$ [6].

Velocity of the fluid flow through the valve opening flow area A_{op} can be expressed by the continuity equation [6] as

$$c_{\mathrm{op}} = \left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}}\frac{1}{A_{\mathrm{op}}} = \left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}}\frac{4}{\pi d^2} \quad (13)$$

and the pressure of fluid in the opening area A_{op} is given from the Bernoulli equation as

$$p_{\mathrm{op}} = p - \frac{\rho_{\mathrm{w}} c_{\mathrm{op}}^2}{2}. \quad (14)$$

The fluid force of the horizontal water jet acting upon the moving vertical plug shaft plate surface is then by applying the momentum principle (1) in form

$$F = \left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}}\rho_{\mathrm{w}}\left(c_{\mathrm{op}} - c_{\mathrm{pl}}\right) + \frac{\pi d^2}{4}\left(p_{\mathrm{op}} - p_{\mathrm{a}}\right). \quad (15)$$

3.3. Third Phase of the Plug Displacement

The third phase of the plug assembly motion represents the free fly off, if the plug displacement x_{pl} is greater than $x_{\mathrm{L}} + d/4$ (see Fig. 6).

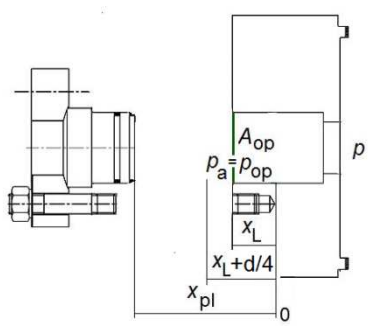

Fig. 6 The third phase of plug displacement

Here, the change in water volume within the valve system is given by the free water discharge through the valve opening flow area A_{op} as

$$\left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}} = \mu A_{\mathrm{op}}\sqrt{\frac{2(p-p_{\mathrm{a}})}{\rho_{\mathrm{w}}}} = \mu\frac{\pi d^2}{4}\sqrt{\frac{2(p-p_{\mathrm{a}})}{\rho_{\mathrm{w}}}}. \quad (16)$$

Velocity of the fluid flow through the valve opening flow area A_{op} is expressed by the same way as in the previous case by Eq. (13).

The fluid force of the horizontal water jet impinging on the moving plug is then given as

$$F = \left(\frac{\mathrm{d}V_{\mathrm{w}}}{\mathrm{d}\tau}\right)_{\mathrm{dis}} \rho_{\mathrm{w}}\left(c_{\mathrm{op}} - c_{\mathrm{pl}}\right). \tag{17}$$

4. Results of Solution

The above described problem was solved numerically using the MATLAB code. Boundary conditions of differential equations solution are fully defined for the above described phases of the plug displacement. The solution of the released plug assembly motion ends when $c_{\mathrm{op}} \leq c_{\mathrm{pl}}$. In this moment, the final speed of plug assembly fly off is reached.

Results of the plug assembly fly off final speed are outlined in Tab. 2 for the input data of solution given in Tab. 1.

Tab. 2 Results of plug assembly fly off final speed

Plug assembly option	1.a / 1.b / 1.c	2.a / 2.b / 2.c	3.a / 3.b / 3.c
Final speed of plug assembly fly off $(c_{\mathrm{pl}})_{\mathrm{fin}}$ [m/s]	30 / 73 / 92	16 / 56 / 67	17 / 60 / 84

Examples of the plug assembly velocity solution in relation to the displacement for the options 1.c and 3.c are shown in Fig. 7, where particular phases of the plug motion and the final speed of plug assembly fly off are specified.

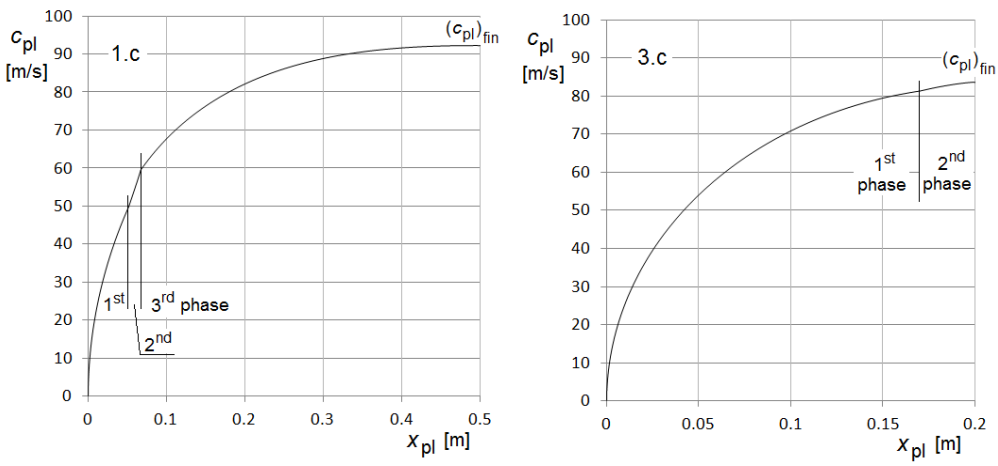

Fig. 7 Velocity of plug assembly c_{pl} related to its displacement x_{pl}

It is apparent that the water discharge process and the course of plug assembly velocity are strongly influenced by the plug dimensions, by the tested valve system inner volume, and by the test pressure. According to these parameters, not all phases of the plug displacement need to take place and the process may end, due to condition $c_{\mathrm{op}} \leq c_{\mathrm{pl}}$, in the first or second phase (see Fig. 7).

The influence of the test pressure on the motion of the plug assembly of option 2.b is shown in Fig. 8 for various test pressures: 80, 100, and 140 MPa.

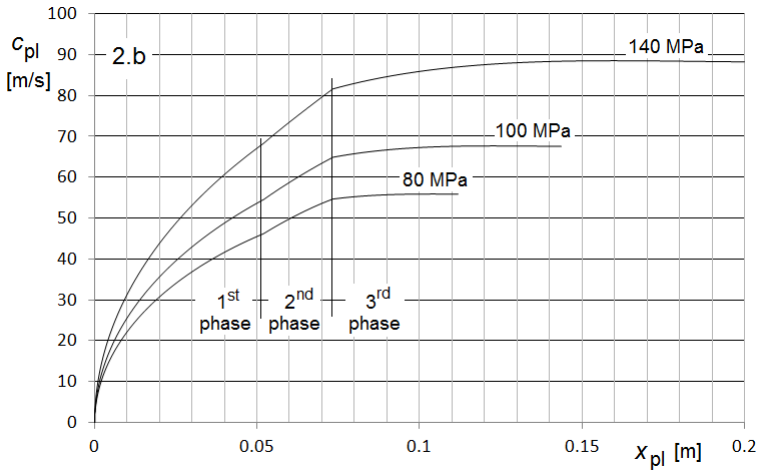

Fig. 8 Influence of test pressure on plug assembly velocity (x_{pl} – plug displacement)

The influence of the tested valve inner volume on the motion of the plug assembly is shown in Fig. 9, where courses of the plug velocity are compared for options 2.a, 2.b, and 2.c, i.e. for 2, 25, and 50 litters.

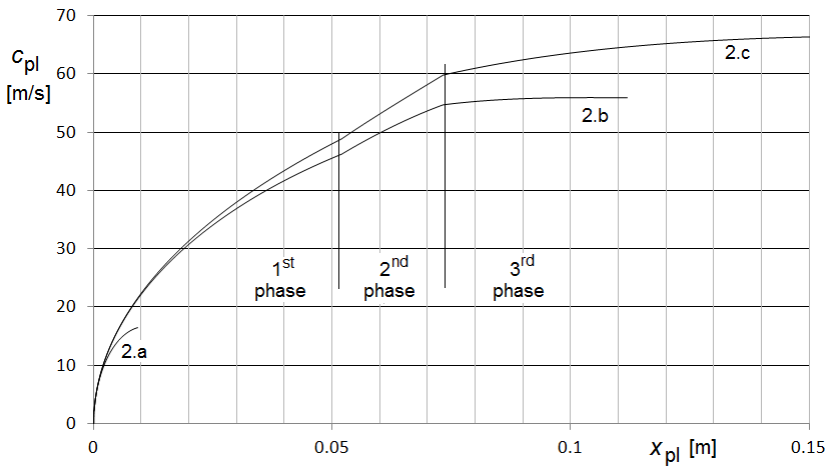

Fig. 9 Influence of valve inner volume on plug assembly velocity (x_{pl} – plug displacement)

5. Conclusions

In this work, a hydrodynamic model for the quasi-dynamic analysis of the released plug motion has been applied for the prediction of speed of plug assembly fly off. This

analysis enables us to understand how the plug assembly mass and dimensions (the opening diameter and the plug shaft length) influence the plug assembly fly off motion as shown in Fig. 7. Further, we can understand the effect of the test pressure (Fig. 8) and the valve inner volume (Fig. 9).

It was found that for such high-pressure system, the influence of the air pocket expansion on the released plug assembly motion is negligible due to the small content of air in the system. In this case, the air pocket represents only 0.026 % of the system volume at the pressure of 140 MPa, 0.03 % at 100 MPa, or 0.06 % at 20 MPa, respectively (see Fig. 3). The influence of the air pocket expansion becomes significant below the pressure of about 5 MPa, but the process of plug fly off ends at substantially higher pressures. Moreover, very high derivatives of the polytropic expansion (7) complicate the numerical solution of the air pocket expansion for high pressures.

Results of the analysis of the released plug assembly motion provide very useful and important data and information for the design of restraint and safety barrier systems.

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