Mathematical modelling of the cryogenic-dynamic start-up process in a pneumatic installation

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Abstract. For studying the kinetic laws of the processes of transitional phase processes of cryo-liquids into the vapor phase, methods of mathematical modelling were used. A mathematical model was developed for the instant boiling up of cryo-liquids using the finite element method. The paper shows the results of a numerical experiment with different amounts of evaporating cryo-liquid in the same temperature range. The dependences of Von Mises pressure and pressure during cryo-liquid evaporation are shown. These studies are necessary for further detailed study of the kinetic laws of the processes of fast-flow phase transitions of cryo-liquids in a pneumatic installation for the cryogenic-dynamic startup of devices.

1. Introduction

In order to convert the potential energy of compressed gas into kinetic energy, it is proposed to generate the energy of evaporation of cryogenic gas instead of heavy and bulky cylinders in pneumatic devices. Compared with classical artillery, the technical result of the idea is expressed in a decrease in the initial hard impact of gases on the projectile and more constant pressure on the projectile along the entire length of the barrel. Compared with the prototype, the peak value of the acceleration of the projectile decreases becomes smoother and more uniform. The study of the mechanisms for the instantaneous evaporation of cryogenic liquids for use in launchers has not yet been studied.

It would seem that such problems can be solved with the help of artillery barrel systems or with the use of small missiles. However, in artillery systems, due to the burning speed of gunpowder, significant shock loads on the rocket inevitably arise, which is unacceptable in the task [1]. Rockets also create significant noise and are visually very visible on the active part of the trajectory, in the daytime due to a smoke plume, and dark time due to the flame of the engine. All these shortcomings are deprived of pneumatic devices. They were even limitedly used in combat operations (pneumatic mortars), though pneumatics is very limited in application because of bulky and heavy cylinders with compressed gas [2]. In addition, powder shots with calibres from 100 mm are not able to use silencers. Acoustic exposure in many tasks may be completely unacceptable. Several similar jobs are known in the cryogenics industry [3-6].

In classical artillery, large-scale studies are underway to develop fuel powders with longer and progressive combustion. Multichannel gunpowder has been developed, but, nevertheless, the values
between the maximum and minimum gas pressures in the barrel differ by a factor of ten. We previously invented a device capable of solving the above problems. A fragment of a pneumatic installation for the cryogenic-dynamic launch of reconnaissance and targeting (fragile) devices, the evaporator is shown in Figure 1a [7].

In the course of the work, it is necessary to conduct studies on the phase transition of liquid nitrogen to the gaseous state under conditions of a closed, and then sharply increasing (exponentially) volume, which is characterized as quasi-isobaric conditions. Evaporation occurs during local, point overheating of liquid gas in a sprayed state. With an increase in volume, the pressure is maintained due to the progressive evaporation of the bulk of the cryo-fluid under turbulent conditions [8-9].

2. Experimental setup
The work compared two cryogenic charges consisting of liquid nitrogen, which was subjected to heat for the cryogenic-dynamic startup of devices. A mathematical model of the evaporator of this device was developed to analyze the subsequent Von Mises and Pressure stresses to conclude the effectiveness of this process. The experimental evaporator is shown in Figure 1a, and a computer model of this device is shown in Figure 1b. The first sample occupied a volume of 0.2 l and the second sample, respectively, 0.4 l.

3. Mathematical Model
The following equation was used for describing thermal expansion[10]:

\[ \rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_f) = \alpha_p T \left( \frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p \right) + \tau : \nabla \mathbf{u} + Q, \]  

(1)

considering that:
the Cauchy stress tensor, \( \sigma \), is split into static and deviatoric parts as in:

\[ \sigma = - \rho \mathbf{1} + \tau, \]  

(2)

the dependent variables are the temperature \( T \), and pressure, \( p \);
where, \( \rho \) is the density [kg/m\(^3\)], \( C_p \) is the specific heat capacity at constant pressure [J/(kg·K)], \( T \) is the absolute temperature [K], \( \mathbf{u} \) is the velocity vector [m/s], \( \mathbf{q} \) is the heat flux by conduction [W/m\(^2\)], \( \mathbf{q}_f \) is

![Figure 1. The image device of the evaporator: a - experimental sample, b - mathematical model.](image)
the heat flux by radiation [W/m²], \( \alpha_p \) is the coefficient of thermal expansion [1/K]:

\[
\alpha_p = -\frac{1}{\rho} \frac{\partial \rho}{\partial T},
\]

(3)

\( p \) is the pressure [Pa], \( \tau \) is the viscous stress tensor [Pa], \( Q \) contains heat sources other than viscous dissipation [W/m³].

In the mathematical model, a heat exchange unit between the radiation of the evaporator and the environment was used. Internal heat flux from the surface to the environment:

\[
-\mathbf{n} \cdot \mathbf{q} = \varepsilon \sigma (T_{amb}^4 - T^4),
\]

(4)

Where \( \varepsilon \) is the surface emissivity, \( \sigma \) is the Stefan-Boltzmann constant (a predetermined physical constant), and \( T_{amb} \) is the ambient temperature (\( \varepsilon = 0.7; \ T_{amb} = 293.15 \) K). The properties of liquid nitrogen are taken from [11-12].

4. Results of Numerical Analysis

The simulation results are presented in Figure 2. The stress distributions according to Von Mises (Fig. 2a, c) and the pressures arising on the surface during evaporation of liquid nitrogen (Fig. 2b, d) are shown. As we can see, the nature of the distribution at different volumes of the sample subjected to heat is different.

![Figure 2](image)

**Figure 2.** Von Mises stress and pressure distributions over sample surfaces. Where: a - is the Von Mises voltage across the surface of the sample with a volume of 0.2 l, b - is the Pressure arising from the heat load of the sample with the volume of 0.2 l, c - is the Von Mises stress over the surface of the sample with the volume of 0.4 l, d - is the Pressure arising from the heat load of the sample with the volume of 0.2 l.
Let us consider the nature of the stress on the surface of the sample in more detail. For this, we construct graphs of the Von Mises stress and pressure along the centre-line of the sample. The resulting material is shown in Figure 3.

Considering the Von Mises stresses along the centre-line of the sample, we can notice the heterogeneity at different volumes of the samples. In Figure 3a we see that the volume of 0.4 l is no longer stable and even 2 times larger. We see a peak value with a volume of 0.4 l, which reaches 9e12 N/m², which is rather strange. On the other hand, with a volume of 0.2 l, we obtain a more uniform distribution of Von Mises voltage and an insignificant loss of power, which subsequently leads to the inappropriate use of a large amount of liquid nitrogen.

Considering the pressure, we can draw the following conclusion. With a large sample volume equal to 0.4 l, we see in Figure 3b, that the same picture is observed as with Von Mises stress. Although in the first case we have a smaller sample volume, we see a more uniform picture, and a pressure of 2e12 Pa is reached, which is enough for throwing a (fragile) device. Under the thermal effect of a large volume of the sample, we see a peak value of -6e12 Pa, as well as a smaller peak of -4e12 Pa, which can tell us that it is necessary to adjust the ignition strategy to edit the heat load.

Figure 3. Dependencies of von Mises and pressure in the sample. a) Mises stress; b) pressure; where: 1 - volume of 0.2 l, 2 - volume of 0.4 l.
5. Conclusion
Based on experimental data, a mathematical model of a pneumatic installation for the cryogenic-
dynamic launch of reconnaissance and targeting (fragile) devices has been developed. In this model,
von Mises stress distributions, and pressure distributions over the surface of the samples were obtained. The data obtained give recommendations on changing the volume of liquid nitrogen for the cryogenic-dynamic start-up. In the future, in the mathematical model, some conditions will be taken into account and refined to approximate real experimental data. These computer models allow a more efficient analysis of the processes occurring during the cryogenic-dynamic startup, and refine the experimental setup based on the data presented by numerical analysis.

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