Computer simulation of thermal expansion of the charge of liquid nitrogen in the process of heat load

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Abstract. The computer simulation model of the expansion of the liquid nitrogen charge during a heat load was created, and the Mises stress criterion was considered on the basis of theoretical and experimental data. The influence of the type of using temperature load was studied to generate calculated numerical data for creating fuel on liquid nitrogen. These studies are necessary for the formation of an additional numerical experiment to study the phase transition of liquid nitrogen to a gaseous state under conditions of a closed, and then sharply increasing (exponentially) volume, which is characterized as quasi-isobaric conditions.

1. Introduction

The serious environmental problems that have arisen today require new technological methods for using various devices and abandoning traditional fuel cells. One of the areas of environmentally friendly alternatives is the use of cryogenic working fluids. Application in space rocket technology, especially in liquid rocket engines, using the cryogenic oxidizing agent and hydrocarbon fuel as fuel, pneumatic units, cryogenic engines, cryogenic systems, gas separators, cryogenic destruction.

There are many projects to create a cryogenic piston engine using cryogenic fluid as a working fluid [1, 2]. The essence of this concept is that with a controlled supply of a cryogenic agent into the liquid, rapid boiling and expansion occurs, which will lead to a sharp increase in internal pressure. Experimental studies on the introduction of a cryogenic agent in water [3–5]. In [3], it was found that a thick vapour layer appears, consisting of a gas that surrounds the cryogenic liquid injected during the phase change, which occurs in the introduced medium. In [4], experiments were carried out on the injection of liquid nitrogen into a relatively large volume of water at an ambient temperature of 293 K. It was recorded that the pressure and rate of increase in pressure increased almost linearly with increasing injection pressure, and reached 2.8 bar and 5.0 bar/s, respectively, at a liquid nitrogen injection rate of approximately 0.85 m/s.

In [5], the cryogenic liquid was supplied into a small-volume vessel (140 ml). The volume of injected cryogenic fluid was small - approximately 2 ml. For example, when liquid nitrogen is injected into water at a pressure of 7 bar, the pressure reaches an amplitude of 14 bar 5 seconds after injection.
2. Experimental setup
In this article, the task is to compare the two types of applied heat load in order to achieve a certain pressure, which must be achieved for the cryogenic-dynamic launch of fragile devices. The first type of heat load will simulate the combustion of an explosive; The temperature profile of the combustion wave is shown in Figure 1. The second type of heat load, which will affect the charge of liquid nitrogen, is the heating of a certain part of the device using induction heating in the temperature range from 0 to 2000 K in 2 s (suppose that with induction heating, the heating rate will change linearly).

![Figure 1. The temperature profile of the wave of combustion of gunpowder based on diethylene glycol dinitrate [6]](image)

For the experiment, I chose a cylinder with a radius of 400 mm and a height of 60 mm. A numerical experiment was carried out using the finite element method. The model was considered as not stationary.

3. Equations
The following equation was used for describing thermal expansion [7]:

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

(1)

considering that:

- the Cauchy stress tensor, \( \sigma \), is split into static and deviatoric parts as in:
  \[ \sigma = -p \mathbf{1} + \tau, \]
  (2)

- the dependent variables are the temperature \( T \), and pressure \( p \);
- where, \( \rho \) is the density [kg/m³], \( C_p \) 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/m²], \( \mathbf{q}_r \) is 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].

The properties of liquid nitrogen are taken from [8-9].

4. The study results obtained using numerical analysis
For studying the comparison of two heating methods, first of all, we compare the speeds and the dependence of the heating of the object, and the pressure over the volume of the simulated sample. Comparative data are presented in Figure 2. As we see the character of increasing pressure repeats the
character of constructing a pressure curve. Figure 2 shows, if it is possible to achieve a linear rise in the temperature of the sample with a high heating rate (1000 K/s), then this method is more controlled, is it not the first heating method, which consists in deliberate burning of explosives. However, it is necessary to analyze the nature of the pressure distribution on the test samples. Figure 3 present the data for this experiment.

Figure 2. Temperature dependence and pressure dependence on time. Where: 1 - Dependence of the maximum pressure in the gas volume at the first type of heat load; 2 - Dependence of the maximum pressure in the gas volume during the second type of heat load; 3 - The dependence of the maximum temperature in the gas volume at the first type of heat load; 4 - The dependence of the maximum temperature in the volume of gas in the second type of heat load.

From the data presented in Figure 3, the distribution pattern of the first and second heating method is significantly different, although the temperature range of heating is the same (0-2000 K). We can see that the pressure level at the final moment is the same, for a more detailed examination we turn to Figure 4.

Figure 3. The pressure distribution over the sample at a time point of 2 s (last time point) [Pa]. a) - The first type of heat load, b) - the second type of heat load.

During the rapid evaporation of a cryo-liquid or in another variant of a gas generator — decomposition of a charged substance, the pressure of the resulting gases entered the reservoir and smoothed out. In addition, the gas-air mixture pushes the projectile along the barrel, and at the same time, due to the additional volume of the tank, the pressure decreases more smoothly. Based on this principle, we will continue research based on an array of experimental data. For studying the kinetic regularity of the processes of fast-flowing phase transitions of cryo-liquids into the vapour phase under various
thermodynamic conditions, a mathematical model was developed for the instant boiling of cryo-liquids in the process of thermal loading by various methods. Analysis of the results shows that the nature of Mises stress varies. The experimental data are shown in Figure 4. An analysis of the simulated data shows (Fig. 4a) that with the second heating method, we observe a smoother voltage distribution. If we consider the nature of the pressure in the sample (Fig. 4b), we can notice that the increase in pressure tends to the centre of the sample, that is, in the first case of heating, then in the second case of heating.

![Graph of Mises stress and pressure](image)

**Figure 4.** Dependencies of von Mises and pressure in the sample. a) Mises stress; b) pressure; where: 1 - the first type of heat load, 2 - the second type of heat load.

5. Conclusion
For the further development and manufacture of a prototype pneumatic installation for cryogenic-dynamic launch of reconnaissance and targeting (fragile) devices, a computer model was analyzed. This model characterized various types of heat load for the application of these studies in further experiments. An analysis was made of two types of thermal load on a liquid nitrogen charge, and the von Mises voltages and pressure by volume are shown. Further studies of the process of liquid nitrogen evaporation under certain conditions make it possible to establish the process of the cryogenic-dynamic launch of reconnaissance and sighting (fragile) devices.

Acknowledgments
The research was supported by the Ministry of Education and Science of the Republic of Kazakhstan. Grants AP08052736 and AP05130123.
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