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Influence of the working fluid properties on water jet cannon efficiency

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ABSTRACT

Fluid flow in water jet cannon for models of ideal incompressible and compressible fluid was investigated. The impact of fluid compressibility on the parameters of water jet cannon of concrete facilities was investigated. Numerical calculations for compressible fluid were performed using Rodionov method. The influence of density and compressibility on water jet cannon parameters was estimated. The distributions of fluid velocity and pressure at different stages of the process were obtained. The parameters that characterize the efficiency of water jet cannon, compared with the corresponding values for the water charge, were calculated. The complex evaluation of water jet cannon efficiency for working fluids with different density and compressibility was performed.

1. Introduction

The technologies, based on liquid jets of high and ultra-high speed, are used for cutting various materials, surface treatment, destruction of rocks and concrete blocks, ammunition disposal, extinguishing the gas flares and so on [1–17]. The effective use of these technologies requires determination of the appropriate design parameters of hydro impulse jet unit, selection of optimal operating modes and parameters of the working fluid for every specific case.

To obtain hydro impulse jets of high speed pulse water cannon and water jet cannon are used on practice [4,18]. These units are determinated by the following principles: fluid displacement from the closed volume through a small hole under a high pressure in pulse water cannon (extrusion) and the acceleration of the fluid flowing into a long convergent nozzle in water jet cannon (inertia).

First designs of pulse water cannon and water jet cannon were created and investigated by Vojtsekhovskij [19]. His theory was based on the model of ideal incompressible fluid and its results coincided badly with the experimental data at high speed of the jet. Based on this theory, Vojtsekhovskij offered exponential profile of water jet cannon nozzle that became widespread and has been patented. W. Cooley used the ideas of Vojtsekhovskij to develop the experimental model of water jet cannon, which was tested in the mining industry for tunneling in hard and very hard rocks [20].

Further development of water jet cannon theory for an ideal incompressible fluid was obtained in [21], which examines the stages of liquid inflow and outflow for the nozzle of exponential form in detail. In [22,23] the flow in water jet cannon was studied numerically and experimentally. The calculations were performed in 1D formulation on Lagrangian movable mesh using the difference scheme with artificial viscosity. During the experiments speed photography of jet was taken and jet head velocity was measured. The results of experiments and calculations for incompressible and compressible fluid coincide suitable for relatively low speed of the jet. The general theory of water jet cannons of different designs and criteria for the evaluation of liquid compressibility in water cannon are presented in [24–27]. The influence of compressibility is estimated by the characteristic time of the process and the Mach number.

The problems of numerical modeling of the fluid in water jet cannons of different designs are considered in [28–32]. Good results give monotonous, conservative numerical methods for second-order approximation, built on the ideas of TVD, ENO, etc., that allow calculations on movable irregular mesh.

Theoretical and experimental studies of water jet cannon and pulse water cannon of various designs are given in [33–37]. In these studies high-speed video filming of pulsed jet was carried out, and the following values were measured: velocity of the jet head, depth and shape of crater in the interaction of the jet with a barrier, pressure in the target. In addition, fluid flow in water jet cannon was calculated in axisymmetric formulation.

The results of theoretical and experimental studies of water jet cannon and pulse water cannon of various designs are summarized in the monographs [4,18]. Various designs of hydro impulse jet

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units, physical principles of their performance, mathematical models of units, numerical methods for solving the equations of motion, the results of calculations, scheme of experiments, experimental equipment, and experimental results, as well as comparison of the theory with experiments and relevant conclusions are described here. The main results presented in monographs, were obtained by the authors.

As the theory and practice show, we can get pulsed liquid jet at a speed of about 3000 m/s by means of water jet cannon and 1500 m/s by means of using water jet cannon. Significant differences in the maximum speed of the pulsed liquid jet in various devices are connected with features of the physical processes occurring in these devices. Pulse water cannon works on extrusion principle of acceleration of a liquid at which the liquid is pushed under high pressure, generated by the piston, through a small hole. Speed of such jet is limited by the strength of unit body.

Water jet cannon works on the principle of inertial acceleration of liquid in which the redistribution of the energy of fluid particles at the leak in converging nozzle occurs. Fluid particles near the free surface are accelerated by the pressure gradient, gaining energy from the bulk liquid, which is inhibited. Therefore in water jet cannon pulsed jet at a speed much higher than in pulse water cannon can be obtained under the same maximum pressure inside the unit.

A different mechanism of fluid acceleration in these units significantly affects such basic hydrodynamic parameters of jets as: the maximum velocity, compact size, range and coefficient of excess pressure. Dependence of these parameters on the nozzle shape and other constructive factors of water jet cannon is investigated in detail in [38]. In this paper the criteria for evaluating the effectiveness of water jet cannon are formulated, and technique of parameter optimization for water jet cannon by changing its construction is proposed.

In work [24–27] the effect of compressibility on parameters of hydro impulsive jet units is estimated. Here a method of slightly compressible fluid is proposed, with which the influence of liquid compressibility on water jet cannon parameters can be traced. It is shown that neglecting the liquid compressibility can lead not only to significant discrepancies in the quantitative results, but also to quality distortion of process. For example, the shock hydro impulsive jet units where wave processes are determining cannot be calculated by the model of an incompressible fluid.

In [39] the viscosity influence on water jet cannon parameters by the method of vanishing viscosity was evaluated. A good coincidence of results of calculation in the exact axisymmetric formulation for the viscous fluid and in the approximate quasi-one-dimensional formulation for ideal fluid was shown. It suggests insignificant impact of fluid viscosity on water jet cannon parameters.

In this paper the flow of fluid in water jet cannon is studied in the framework of models for ideal incompressible and compressible fluid. The effect of liquid compressibility on water jet cannon parameters is estimated on specific facilities. It is shown that the preliminary calculations of water jet cannon parameters can be carried neglecting compressibility. Numerical calculations for compressible fluid are conducted in work [40] by Rodionov method generalized for calculation of compressible flow of liquid in water jet cannon. The influence of fluid density and compressibility on water jet cannon parameters was assessed. The distributions of fluid velocity and pressure at different stages of process are obtained. Parameters characterizing water jet cannon efficiency (the maximum jet velocity, the maximum pressure in the nozzle, the momentum of high-speed section of the jet, the overpressure coefficient, the energy conversion coefficient) are calculated and compared with the corresponding values for water charge. The complex evaluation of water jet cannon efficiency for working fluid with different density and compressibility was conducted.

2. Model of incompressible fluid

Let's consider the inflow of water charge in converging nozzle. Suppose that the water charge 2 of length L moves with piston 1 at u_0 velocity through a cylindrical barrel 3 and at the initial start time to inflow into the converging nozzle 4 (Fig. 1).

When liquid inflows into converging nozzle, due to internal pressure forces, redistribution of energy occurs, which results in acceleration of fluid particles near the leading edge and slowing down of the piston and the bulk fluid [4,41]. This process leads to multiple acceleration of frontal liquid particles. This process leads to multiple acceleration of frontal liquid particles, which form at the expiration a pulse liquid jet of ultrahigh velocity (ultra jet).

Numerous theoretical and experimental studies of hydro impulse jet units overviewed in the introduction; show that the flow in water jet cannon can be considered in the 1D gas-dynamic model with sufficient accuracy for practical purposes. In this model, the liquid is considered to be ideal and compressible, the flow is one-dimensional, the air influence in the nozzle and the deformation of the unit's body is not taken into account, the boundary between the media are considered to be flat. Fluid flow in the water jet cannon in the framework of this model is described by a system of partial differential equations of hyperbolic type that can be solved only numerically. For simplicity, we can neglect the compressibility of the fluid and reduce the problem to ordinary differential equations. These two models are used in this paper to calculate the parameters of the water jet cannon.

In the framework of ideal incompressible fluid model, the equations for quasi-one-dimensional unsteady flow in water jet cannon are written as follows:

$$\frac{\partial uS}{\partial x} = 0, \tag{1}$$

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left(\frac{u^2}{2} + \frac{p}{\rho}\right) = 0. \tag{2}$$

where u, p and ρ – velocity, pressure and density, x and t – coordinate and time, $S = S(x)$ – cross-sectional area of the nozzle that one is a set function of the coordinate x. The origin of coordinates coincides with the trailing edge of the water charge.

The initial and boundary conditions for water jet cannon are the following:

$$u(0,x) = u_0, \quad p(0,x) = 0, \quad -L \leqslant x \leqslant 0, \quad x_R(0) = -L;$$
$$x_F(0) = 0, \quad u(t,x_R) = u_R, \quad p(t,x_F) = 0,$$

where u_0 – initial velocity of water and piston, x_R, x_F – coordinates of the leading and the trailing edge of the water charge, u_R – velocity of the trailing edge, L – length of water charge. Indices "R" and "F" indicate parameters on the trailing and the leading edges of the water charge.

Let's divide the water jet cannon shot in two stages: the fluid inflow into converging nozzle and the outflow of a pulsed jet from the nozzle.

Stage of inflow, which begins the water jet cannon shot, ends when the leading edge of the liquid reaches the nozzle section. The mass and energy balances on the stage of inflow are:

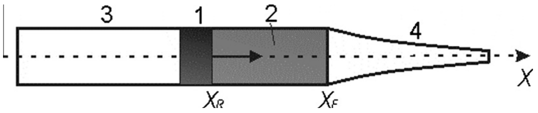

Fig. 1. Water jet cannon. 1 – piston; 2 – water charge; 3 – cylindrical barrel; 4 – nozzle.