Water jet cutting resistance

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Abstract. The main purpose of the study was establishing the coefficient of hydraulic resistance of two-phase flow using in water jet cutting. In waterjet cutting (JWC) and in abrasive waterjet cutting (AJWC), a two-phase flow consist of water and abrasive solid particles, moves at a high mean velocity (more than 8.0 m/s). Such flows differ from natural and well-studied flows in hydraulic transport. The aim of this work is to investigate experimentally the additional pressure losses during transportation of the abrasive. For the experimental research were used. The supply of fire extinguishing agents is carried out along the sleeve lines, and, as is known, there are pressure losses. In this regard, the problem arises, at what maximum distance from the pumping unit is possible to supply fire extinguishing agents in the form of water and a mixture of water and abrasive particles, and how pressure losses occur in this case, because the flow rates and working pressure of fire extinguishing systems with waterjet cutting are high enough (the working pressure is 30 MPa). The loss of pressure during transportation depends on the flow rate, its viscosity, pipeline characteristics, etc. The results of field studies to determine the basic kinematic characteristics of the two-phase flow are presented. The combination of these parameters is largely characterized by the coefficient of hydraulic friction, which is insufficiently studied for the systems under consideration. As a result of the obtained experimental data, based on the Darcy-Weisbach equation, the coefficient of hydraulic friction was determined, the value of which was 0.019. The coefficient of local resistance was 0.45.

1. Introduction

In waterjet cutting, a two-phase flow consisting of water and abrasive solid particles moves at a high mean velocity. Destruction of hard materials and alloys requires a large force and therefore a high flow rate. Such flows differ utterly from natural and well-studied flows in hydraulic transport and hydroprocessing. Determination of kinematic characteristics in the waterjet cutting is an independent task.

Additional losses (pressure losses) occur when a two-phase flow is moving. Amount of pressure loss is influenced by many factors (from the physical properties of the flow to the characteristics of the pipeline). When considering multiphase flows (in this paper – two-phases), additional losses occur as a result of the interaction of their transfer phases:

\[ i_c = i_0 + \Delta i \]

where for relative losses: \( i_c \) – two-phases flow losses, dimensionless; \( i_0 = \frac{1}{d} \frac{\lambda v^2}{2g} \) - Darcy-Weisbach equation, \( i_0 \) - losses in water flow, dimensionless, \( d \) – diameter of pipeline, \( m \), \( v \) – mean flow velocity,
m/sec; Δι - additional losses due to the presence of solid particles in the flow (relative losses – divided for length for dimensionless).

The following equation is used to calculate additional pressure flow losses:

\[ \Delta i = \delta \sqrt[3]{j} \sqrt{c_0} \frac{V_{cr}}{V}, \]  

(2)

where \( \delta \) – coefficient taking into account the effect of relative particle size relative to pipe diameter \( D/d \); \( j \) -coefficient of graininess particles; \( C_0 \) – the actual volumetric texture, N/m³; \( V_{cr} \) - the critical velocity of a mixture in which particles begin to move along the flow, m/s; \( V \) – flow velocity, m/s.

The minimum velocity at which a stream of hot water can transport solid particles is called the critical velocity and is determined by formula 3:

\[ V_{cr} = 8.3 \sqrt{D} \sqrt{C_0 \psi_*}, \]  

(3)

where is \( D \) - the tube diameter, m; \( \psi_* \) - transportability coefficient, which characterizes the ability of solid particles to be transported by water flow, which is a function of hydraulic size \( \psi_* = f(W) \).

2. Literature Reference

Waterjet cutting is used in many fields of activity [1, 2]. It has found its application in firefighting. Flow motion in waterjet cutting is the movement of a two-phase flow containing a solid phase (a mixture of abrasive particles Mg, Fe₂SiO₄ – 62-76%, Fe, Al, Ca, SiO₂ – 20-35%, Fe₃O₄ – 1-2%) of no more than 4% of the volume of water and liquid (water). The peculiarity of this flow is also that the mean velocity is high enough for natural and engineering flows (it is approximately in the range from 6.0 to 8.0 m/s) [3-9].

According to statistics, the majority of modern fires occur in rooms that represent a closed volume (modern apartments, hangars, compartments, etc.). Modern decoration of many premises of buildings and structures is expressed by the presence of polymer materials that have a higher heat of combustion and with sufficient ventilation, a high level of heat release compared to traditional materials.

The use of modern double-glazed windows and sealed doors in the premises keeps the probability that the fire will go into a mode when only oxygen is not enough for burning. Such fires are fraught with dangerous phenomena associated with the emission of flames, which is the cause of injuries and the spread of fire [10].

To minimize the occurrence of dangerous phenomena and effectively extinguish the fire, fire extinguishing systems with waterjet cutting capabilities have been developed, which allow the supply of extinguishing agents to the burning closed volume without violating its integrity.

Effective firefighting is achieved by saturating the burning volume with water in the atomized state (the average diameter of the drops does not exceed 200 microns), when it enters the zone with a high temperature, it evaporates, thereby diverting a significant amount of heat energy from the burning zone [11-13].

The considered method of fire-fighting has recently been increasingly introduced and used for firefighting purposes [14,15]. However, the effectiveness of the fire extinguishing method under consideration depends on many factors, one of which is the pressure in front of the barrel (spray nozzle), which affects both the degree of cutting of structures and the formation of drops of a certain size [16].

The supply of fire extinguishing agents is carried out along the sleeve lines, and, as is known, there are pressure losses. In this regard, the problem arises, at what maximum distance from the pumping unit is possible to supply fire extinguishing agents in the form of water and a mixture of water and abrasive particles, and how pressure losses occur in this case, because the flow rates and working pressure of fire extinguishing systems with waterjet cutting are high enough (the working pressure is...
30 MPa). The definition of these features will largely depend on the tactics of fire extinguishing systems [17-20].

3. Methods

The method of research is experimental. To study the pressure losses, a measuring system was developed experimentally, some elements of which are shown in figure 1.

**Figure 1.** Experimental system. a) 1-fire truck with fire extinguishing system; 2-80.0 m long hose line; 3-installation barrel; 4-sleeve inserts with pressure transducers; 5-multi-channel RTM 59 process recorder; 6-connecting cable lines. b) Sleeve inserts with media separators, valve blocks and pressure sensors.

Losses are divided into local and losses by length:

\[ h_{\text{total}} = h_{\text{length}} + \sum h_{\text{local}} \]  

(4)

In both cases, the cause of the pressure loss is the strength of the viscosity, with the loss of pressure along the length, the energy is spent on overcoming the resistance to friction against the surface of the pipeline. Local pressure losses occur in areas where flow deformations occur and are caused by energy costs for recovery (due to deformation) in viscous flows of the velocity distribution.

The main formula for determining the losses along the length is the Darcy-Weisbach formula and for local loss:

\[ i_{\text{local}} = \frac{h_{\text{local}}}{l} = \xi_{\text{local}} \frac{V^2 \rho_m}{2gl \rho} \]  

(5)

where \( \xi_{\text{local}} \) - the coefficient of local hydraulic resistance; \( \rho_m \) - the density of the mixture, kg/m\(^3\); \( \rho \) - the density of water, kg/m\(^3\).

For experimental research local and losses by length laying the pipeline in a straight line and with curves in order to create local resistances and bring the operating conditions closer to the real ones. Experiments were carried out for pure water and for a mixture. A series of experiments was performed when creating local resistances expressed by bending the line at a certain angle (figure 2).

**Figure 2.** Measurement of overpressure at the pipeline and study of local resistances (90 (a) and 180 (b) degree rotation).
Taking into account the operating parameters of the fire extinguishing system with waterjet cutting and its technical features (the diameter of the inner section of the sleeve is 12 mm), we can conclude that in engineering hydraulics, the issue of determining the coefficient of hydraulic friction in the systems under consideration is quite complex. The main characteristics defined by the field method shows in table 1.

| Value                                           | Formula | Amount  | Note                                      |
|-------------------------------------------------|---------|---------|-------------------------------------------|
| The average particle size of the solid particles, $d_i$ (mm) | $-$     | 0.3 – 0.8 | Requirement of cutting technology          |
| Coefficient of graininess $J$ ( - )              | $-$     | 2       | It is obtained as a result of sieve analysis |
| Weighted average density of solid particles, $\rho_p$, (g/cm³) | $\rho_p = \frac{\sum \rho_i \cdot n}{100\%}$ | 4.34 | $\rho_i$ - density of solid particles, $n$ - % content of solid particles in the abrasive composition |
| The actual two phases flow (mixture) density $\rho_m$, (g/cm³) | $\rho_m = \int_{\omega} \rho \cdot u \cdot d\omega$ | 1.14 | $\rho_i$ and $u_i$ accordingly, the density and velocity are local, determined for each part of the flow cross section (segment) |
| Two phases flow rate $Q_m$, (cm³/sec)            | $Q_m = \frac{W_m}{\omega}$ | 1.066 | The volume of the mixture flowing through the cross section of the pipe per unit of time |
| Mean two phases flow velocity $V_m$, (cm/sec)    | $V_m = \frac{Q_m}{\omega}$ | 943.6 | $\omega$ - cross section $1.13 \text{ cm}^2$ ($D = 12 \text{ mm}$) |
| The actual the volume consistency of the flow $C_0$, ( - ) | $C_0 = \frac{\rho_m - \rho}{\rho_p - \rho}$ | 0.04 | $\rho$ - water density |

4. Results

Experiment data on additional energy losses associated with the presence of solid particles are obtained. The results of measurements of pressure losses during the supply of the mixture in the straight and curved laying of pipelines shows in figure 3.
Mixture resistance was 0.45.

The level of reliability showed that the confidence interval in all experiments contains the true value of the studied value. In the case of a normal distribution, the probability that a random variable will take values in the studied interval.

The most important requirement for statistical data is its reliability, i.e. the data is consistent with what it actually is. In the case of a normal distribution, the probability that a random variable will take values in the studied interval. The level of reliability showed that the confidence interval in all experiments contains the true value of the studied value.

As a result of the obtained experimental data, based on the Darcy-Weisbach equation, the coefficient of hydraulic friction was determined, the value of which was 0.019. The coefficient of local resistance was 0.45.

**Table 2.** Characteristics of experimental data.

| Stream                              | Value                                      | $P_{av}$ | $\pm p$ | max  | min  | $\sigma$ | $S$  | $Var(p)$ | $E$  | $A$  |
|------------------------------------|--------------------------------------------|----------|---------|------|------|----------|------|----------|------|------|
| water, straight pipeline            | Pressure at the beginning, MPa            | 32.55    | 0.32    | 32.68| 32.07| 0.1      | 0.02 | 0.01     | -1.15| -0.44|
|                                    | Pressure at the end, MPa                  | 30.03    | 0.31    | 30.16| 29.52| 0.1      | 0.02 | 0.01     | -1.32| -0.43|
|                                    | Losses, MPa                               | 2.52     | 0.13    | 2.64 | 2.61 | 0.02     | 0.00 | 0.00     | 4.92 | 1.67 |
| two-phase flow (mixture), straight pipeline | Pressure at the beginning, MPa        | 33.15    | 0.37    | 33.47| 32.06| 0.11     | 0.08 | 0.13     | 2.79 | -1.76|
|                                    | Pressure at the end, MPa                  | 30.57    | 0.36    | 30.9 | 29.52| 0.13     | 0.08 | 0.13     | 3.06 | -1.83|
|                                    | Losses, MPa                               | 2.58     | 0.04    | 2.66 | 2.48 | 0.04     | 0.01 | 0.00     | 1.64 | -1.19|
| water pipeline with curves          | Pressure at the beginning, MPa            | 32.48    | 0.23    | 32.58| 32.34| 0.05     | 0.01 | 0.00     | 0.36 | -0.60|
|                                    | Pressure at the end, MPa                  | 29.95    | 0.24    | 30.06| 29.81| 0.05     | 0.01 | 0.00     | 1.39 | -0.54|
|                                    | Losses, MPa                               | 2.53     | 0.03    | 2.54 | 2.51 | 0.01     | 0.00 | 0.00     | -0.95| -0.23|
| two-phase flow (mixture) pipeline with curves | Pressure at the beginning, MPa    | 33.33    | 0.31    | 33.52| 33.20| 0.08     | 0.02 | 0.00     | -0.59| -0.60|
|                                    | Pressure at the end, MPa                  | 30.73    | 0.31    | 30.92| 30.61| 0.08     | 0.02 | 0.00     | -0.21| -0.21|
|                                    | Losses, MPa                               | 2.60     | 0.05    | 2.63 | 2.58 | 0.01     | 0.00 | 0.00     | -0.79| -0.79|

In table 2 shows main statistical characteristics for experimental data. Were $\pm p$ - range of pressure value, $\sigma$ – standard deviation, $S$ – standard error, $Var(p)$ – variance, $E$ – excess, $A$ - skewness.
The coefficient of local resistances obtained from the calculation results in table 2 is the sum of six local resistances

\[ \sum \xi = 2\xi_{\text{twist}} + 4\xi_{\text{twist}} = 10\xi_{\text{twist}} \quad (6) \]

Therefore, the coefficient of local resistance for the sleeve line resistance type: smooth 90-degree twist rotation was 0.04.

5. Discussion
The movement of a two-phase flow is a rather complex process that is influenced by many factors. Flow characteristics may depend on the physical properties of the moving medium, as well as on the properties of the pipeline, flow rates, etc.

In this regard, it is quite difficult to determine the characteristics of a moving stream, especially to assess its economic capabilities. However, thanks to scientific and experimental research, it is possible to determine the characteristics of the flow, which in the future allow it to be calculated and based on these calculations, to design and operate engineering systems.

The average values for pressure losses during transportation of water and mixture are shown in table 3.

| Type of pipeline | Pressure losses by length, MPa | Darcy-Weisbach coefficient \( \lambda \) | Local pressure losses, MPa | Coefficient of local resistance \( \xi_{\text{local}} \) |
|------------------|-------------------------------|---------------------------------|---------------------------|---------------------------|
| Water straight   | 2.52                          | 0.018                           | -                         | -                         |
| Mixture straight | 2.58                          | 0.019                           | -                         | -                         |
| Water curves     | 2.53                          | -                               | 0.00421                   | 0.09                      |
| Mixture curves   | 2.60                          | -                               | 0.02294                   | 0.45                      |

This work presents the results of experimental studies of the head loss of a two-phase flow consisting of water and solid abrasive particles. As a result, based on the experimental and calculated data obtained, it was possible to establish that the value of additional losses arising during transportation of solid particles is about 0.0056 m per one meter of the sleeve line.

The calculated value of the head loss during transportation of the mixture was 3.1836 m per meter of the sleeve line. The total value of pressure losses over the entire section of the sleeve line (taking into account the density of the mixture) was 2.736 MPa, which is consistent with the data obtained experimentally. However, in order to obtain and establish more accurate values of the hydraulic characteristics of the systems under consideration, it is planned to conduct more than one series of experiments in the future.

At the moment, based on the results obtained, the range of fire extinguishing agents was determined, the value of which for water was 317.0 m, for the mixture – 290.0 m.

References
[1] Gergel' V I and Meshalkin E A 2017 Fire and explosion safety 3 45-49 [in Russian].
[2] Karpyshhev A V, Dushkin A L, Gluhov I S and Segal' M D 2006 Safety and emergency Issues 5 34–44 [in Russian].
[3] Methodical recommendations on tactics of application of the cars equipped with installations of fire extinguishing with possibilities of waterjet cutting 2017 EMERCOM of Russia in Moscow [in Russian].
[4] Gsell J 2010 Assessment of fire suppression capabilities of water mist. Fighting Compartment Fires with the Cutting Extinguisher 138.
[5] Liao W and Deng X 2017 MSETEE Earth and Environments Science. 1-5 DOI:10.1088/1755-
1315/81/1/012167.

[6] Li D Q 2016 *International Journal of Oil Gas and Coal Technology* 518-525.
[7] Gibilaro L, Gallucci K, Di Felice R and Pagliai P. 2007 *Chemical Engineering Science* 62 294–300.
[8] Bayer I S and Megaridis C M 2006 *J. Fluid Mechanics* 558 415 – 449.
[9] Song D, Wang E, Liu Z, Liu X, and Shen R 2014 *International Journal of Rock Mechanics and Mining Sciences* 318-331.
[10] Bobkov S A, Baburin A V and Komrakov P V 2014 *Physical and chemical bases of development and extinguishing of fires Moscow: EMERCOM of Russia in Moscow* 210 [in Russian].
[11] Gusev I A and Aleshkov M V 2017 *Provision of fire extinguishing technology in confined spaces of energy facilities. Security system* 176–179 [in Russian].
[12] Gergel' V I and Meshalkin E A 2017 *Fire safety* 3 45-49.
[13] Karpyshev A V, Dushkin A L, Gluhov I S and Segal' M D 2006 *Security and emergency issues* 5 34–44 [in Russian].
[14] CHugaev R R 2013 *Hydraulic* 672 [in Russian].
[15] Shahid A and Uijttewaal W S J 2008 *Journal of Hydraulic Engineering* 325-330 DOI: 10.1061/(ASCE)HY.1943-7900.0000671.
[16] Berzi D and Larcan E 2013 *Journal of Hydraulic Engineering* 187-194 DOI: 10.1061/(ASCE)HY.1943–7900.0000664.
[17] Hotta N, Miamoto K 2008 *International Journal of Erosion Control Engineering* 1(2) 54-61.
[18] Abrosimov YU G 2005 *Hydraulic* EMERCOM of Russia in Moscow 312 [in Russian].
[19] Berzi D, Di Prisco C G and Vescovi D 2011 *Physics review* 84(3) 547-549.
[20] Mitrai N and Nakanishi H 2007 *Physics review* 75(3) 301-305.