Study of energy parameters of machine parts of water-ice jet cleaning applications

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Abstract. The reader will achieve a benchmark understanding of the essence of cleaning for the removal of contaminants from machine elements by means of cryo jet/water-ice jet with particles prepared beforehand. This paper represents the classification of the most common contaminants appearing on the surfaces of machine elements after a long-term service. The conceptual contribution of the paper is to represent a thermo-physical model of contaminant removal by means of a water ice jet. In conclusion, it is evident that this study has shown the dependencies between the friction force of an ice particle with an obstacle (contamination), a dimensional change of an ice particle in the cleaning process and the quantity of heat transmitted to an ice particle.

1. Introduction
The hydro jet technologies are widely used in industry. They are necessary for cutting materials, cleaning contaminants off the surfaces of machine elements, varnish removal, blasting of thin bores etc. [1 - 16].

2. Problem description
During an operation of machine elements contaminants (which differ in kind, composition, properties and the strength of the adhesion to the surfaces of machine elements) are being formed on their outer and inner surfaces. These contaminants reduce their durability, service life and resistance to corrosion.

   When repairs are carried out, contaminants undermine labour productivity, accuracy of monitoring and defectation of machine elements, reduce repair quality and resource of repaired machines and their elements.

   The most widespread causes of contaminative coating formation include an emulsive and oil slick, an introduction of the contaminants from the environment, thermal decomposition of oils, an oxydation of metal surfaces, burnt-on (sticking) sand, oil remains, scale etc.

   Contaminants on the objects under repairs are divided into the following types due to their chemical composition:
- organic (oil and fat deposit, varnish coating films, lubricants);
- non-organic (scale, road mud, corrosion products);
- mixed (carbon deposit, varnish, grease, industrial contaminants).

Contamination of plant items, assembly units and machine elements include:
- outer deposit,

- remains of lubricative materials,
- carbon deposit (building-up),
- corrosion products,
- scale,
- remains of old paint coatings.

The most common and widespread contaminants are remains of fuel-lubricative materials and products of their transformation. Drastic changes of lubricative materials, occurring during use of machines, are caused by the processes of 'aging'-oxidation and polymerization. The following types may be singled out:

1. incomplete combustion of fuel,
2. oxidation products,
3. products of destruction of hydrocarbons,
4. polymerization products,
5. products of condensation and coagulation of hydrocarbon and heteroorganic compound,
6. corrosion products and biodamage of metals in the medium of remains of fuel-lubricative materials.

According to up-to-date state of the field under discussion, the industrial processes must be environment-friendly, energy-efficient and meet industry and evolving governmental regulations. These demands are also obligatory for cleaning for the removal of contaminants from surfaces.

Water jet methods are considered to be the most highly promising and universal methods of cleaning among existing ones.

At the same time, a hydroabrasive cleaning with sand and similar materials, performing the function of an abrasive has a wide range of drawbacks. Let us mention some of them:

- the abrasive complicates cleaning of inner and inaccessible surfaces;
- roughening of clean surfaces;
- the necessity of utilization of the abrasive, contaminated during the blasting process;
- a high cost of an abrasive material and its delivery.

Therefore, renewal and replacement of the abrasive material is absolutely necessary for a wide introduction of hydroabrasive technology of cleaning machine elements.

Moreover, water-ice jet cleaning technology is not only an ecologically clean but also cost-saving method.

Ice particles possess properties of hard particles, which allow them to remove a great deal of contaminants during accelerating to higher speeds and avoid causing damage to a base of surfaces, undergoing cleaning. Use of water and ice makes regeneration of clean media easier.

In comparison with other methods of cleaning, water-ice jet technology obtains some advantages:

1 minimization of harmful impact upon environment;

2 a low-cost cleaning materials;

3 an absence of the necessity to transport and keep large amounts of the abrasive material;

4 a possibility of a closed and waste-free cycle;

5 a reduction in an abrasive influence on material;

6 the abrasive does not block up peep-holes of machine elements joints;

7 an absence of dust in the cleaning process;

8. a high durability of an instrument.

The following main stages can be distinguished in the process of a water-ice jet formation:

1. 1. The water jet coming out under high pressure from the jet-forming nozzle creates a vacuum space in the mixing chamber. As a result, ice particles are carried away into the chamber from the supply pipe.

2. In the mixing chamber, ice particles are being brought in by a water jet and being mixed with the water flow. There is also an intensive heat transfer in the chamber.

3. A mixture of water and ice particles is accelerated in the collimating device.

Based on the data on the water-ice jets study reflected in the different literature sources, the main factors and indices determining and characterizing the process of water-ice jet cleaning were formulated. Typically, they fall into 4 categories:

1) hydraulic: water pressure P_0 prior to entering the jet-forming nozzle, diameter d_0 of the jet-forming nozzle (determines the flow rate of high-pressure water Q_0), the rate of water outflow from the nozzle is V_0;

2) geometric: length l_{mc} and diameter d_{mc} of the mixing chamber, diameter d_k and length l_k of the collimating device; the diameter of the orifice of the ice particle feeding system is d_a (determines the mass flow of ice particles Q_a);

3) operating: speed V_n of the tool motion relative to the material, the geometric dimensions of the ice particles, the concentration of ice particles in water jet c, distance l_0 between the section of the collimating device and the material surface;

4) mechanical properties of the material

In order to study the structure of the water-ice jet, as well as the process of water-ice jet cleaning, experimental studies were conducted on a special test bench consisting of the following main units: a high-pressure pump unit of multiplier type 1, hydrojet tool 2 with the possibility of connecting to the ice particle feeding system (not shown in the picture), a movable table with brackets for holding samples 3 (Figure 1), flexible tubing 4. The pumping unit of the bench produces water pressure up to 100 MPa and regulates its flow rate to 30 l/min.
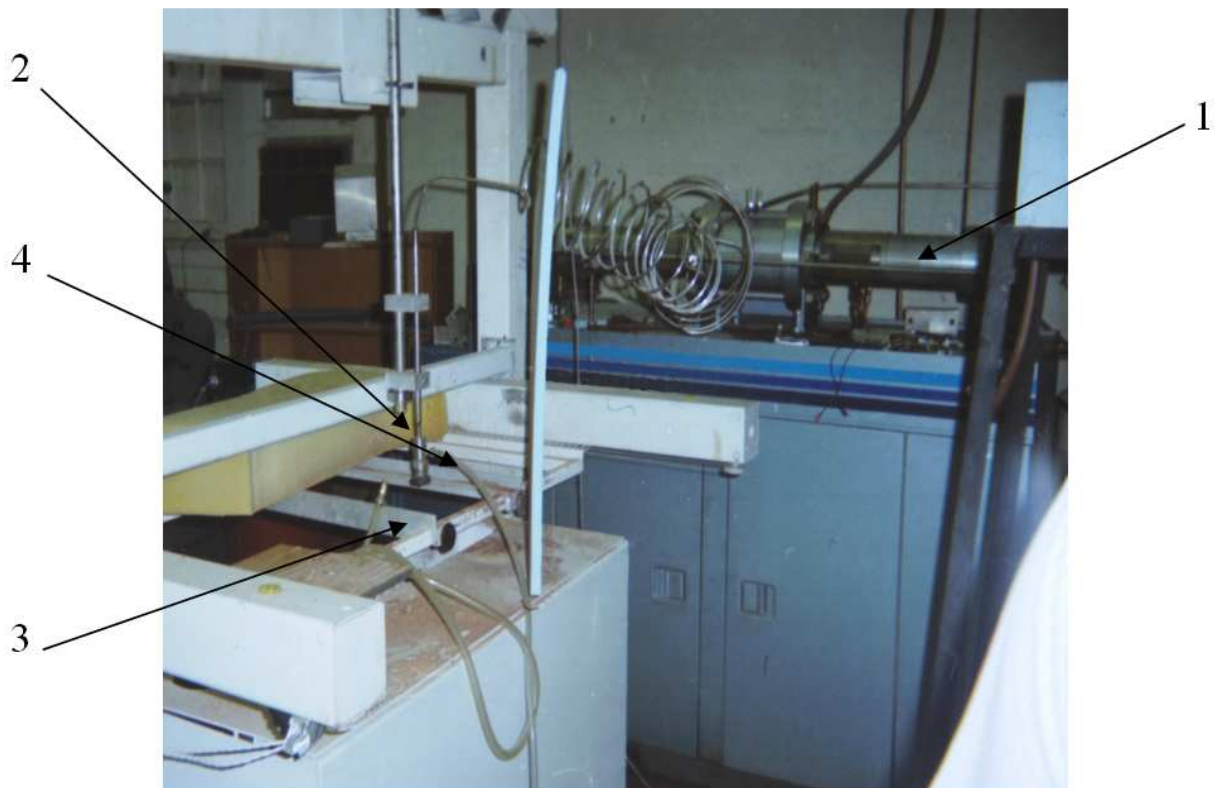

Figure 1. Test bench.

The efficiency of the hydrojet-based fracture process is largely determined by the quality of the jet-forming nozzle. In conducted studies, the jet-forming nozzles manufactured by Procer (France) (Fig. 2) were used with discharge coefficient μ of 0.3 to 0.7. The diameter of the jet-forming nozzles, d_0, was: 0.3, 0.4, 0.5 and 0.6 mm.
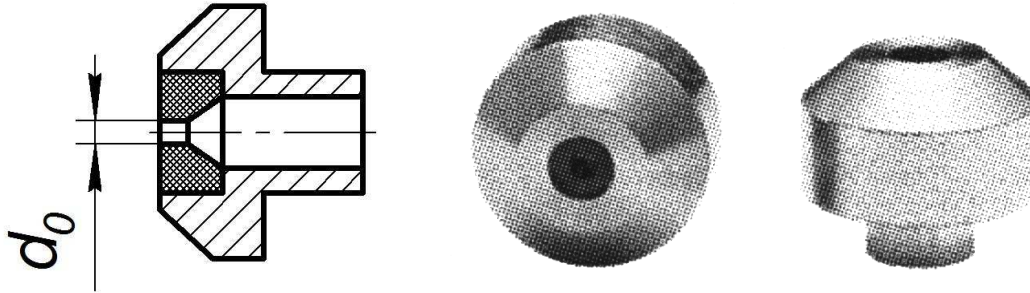

Figure 2. "Procer" jet-forming nozzle

The structure of the high-pressure water-ice jet is divided into three main sections:

• The 1st section - a one-piece section where there are no air bubbles and the fluid velocity is constant.

• The active (main) section consists of a continuous core, individual droplets and ice particles but at a slower rate.

• A section consisting of a mixture of air, individual droplets and ice particles. The section does not have enough energy and speed for the cleaning process.

The main criteria for assessing the effectiveness of the water-jet cleaning process were: the rate of increment in the area of cleaned surface S_0, the width of the interaction region of the jet with the surface to be cleaned (the width of the jet trace), b, and the specific energy intensity of process $E_0^/$.

The rate of increment in the area of cleaned surface S_0 (m²/sec) was determined by the formula:

$$S_0 = bV_n, \tag{1}$$

where: b - the width of the interaction region of the jet with the surface to be cleaned (the width of the jet trace), m;

V_n - the tool movement velocity, m/sec.

Specific energy intensity of cleaning process $E_0^/$ (MJ/m²) was determined by the formula:

$$E_0^/ = \frac{N_h}{S_0}, \tag{2}$$

where N_h - supplied hydraulic power, kW. In turn, the supplied hydraulic power was determined by the formula:

$$N_h = 10^3 P_0 Q_0, \tag{3}$$

where: P_0 - water pressure prior to entering nozzle, Mpa;

Q_0 - water flow rate through the jet-forming nozzle, m³/sec.

Water flow rate Q_0 was calculated using the formula:

$$Q_0 = \pi \frac{d_0{}^2}{4} \left(1.4 \cdot 10^{-5} \cdot \mu_0 \sqrt{10.2 \cdot P_0} \right), \tag{4}$$

where: d_0 - diameter of the jet-forming nozzle, mm;

μ_0 - discharge coefficient (for this case assuming for all nozzles that $\mu_0 = 0.75$).

In order to control the accuracy of the calculations made using formula (4), direct measurements of the flow rate were periodically conducted by collecting water in a measuring container.

In addition, the purification efficiency considering the thickness of the material to be removed is of practical interest (with the ratio of the thickness of the material to be removed to the diameter of the jet-forming nozzle being $\frac{h}{d_0} \geq 1$). In this case, the main criteria for assessing the effectiveness of the process were: thickness of the material to be removed h, rate of increase in the volume of material to be removed W_0 and specific energy intensity of cleaning process E_0.

The rate of increase in the volume of the material to be removed W_0 (m³/sec) was determined by the formula:

$$W_0 = hS_0, \tag{5}$$

The specific energy intensity of cleaning process E_0 (MJ/m²) was determined by the formula:

$$E_0 = \frac{N_h}{W_0}, \tag{6}$$

At the first stage of the study, the structure of the jet was analyzed to determine the influence of various parameters on the length of the part of the jet stream that performs the main operation i.e. the cleaning with the greatest productivity. This part in the structure of the jet stream is called the "active section" - l_{as}.

As a method for studying the structure of the water-ice jet, a method of locating the traces of the jet stream on a surface of special three-layer samples of different hardness sensitive to the mechanical action was used.

The studies were conducted while varying water pressure P_0 from 30 to 60 MPa, with a sample velocity of $V_n = 0.1$ m/sec.
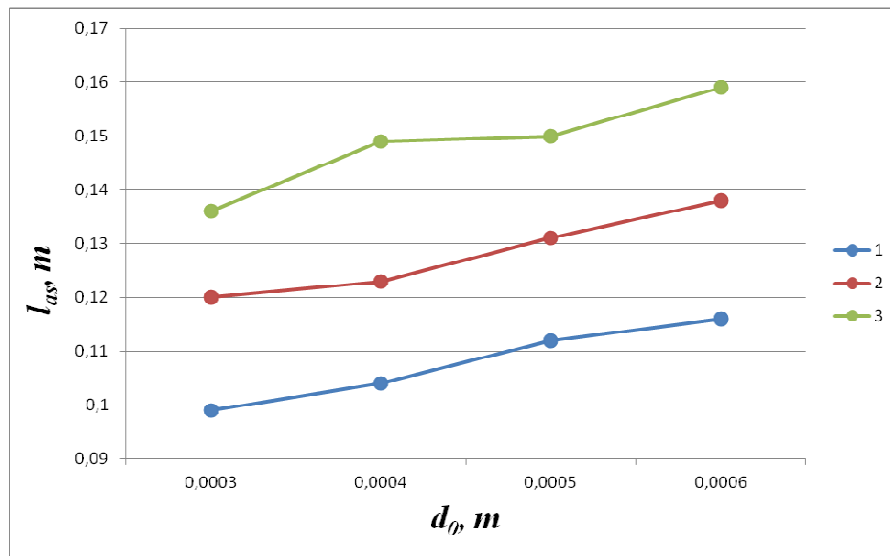
Figure 3. Effect of the water pressure and jet-forming nozzle diameter on the length of the active section of the jet: 1 - $P_0 = 30$ MPa; 2 - $P_0 = 40$ MPa; 3 - $P_0 = 50$ MPa; $\dfrac{d_k}{d_0} = 3$; $\mu = 0.6$.
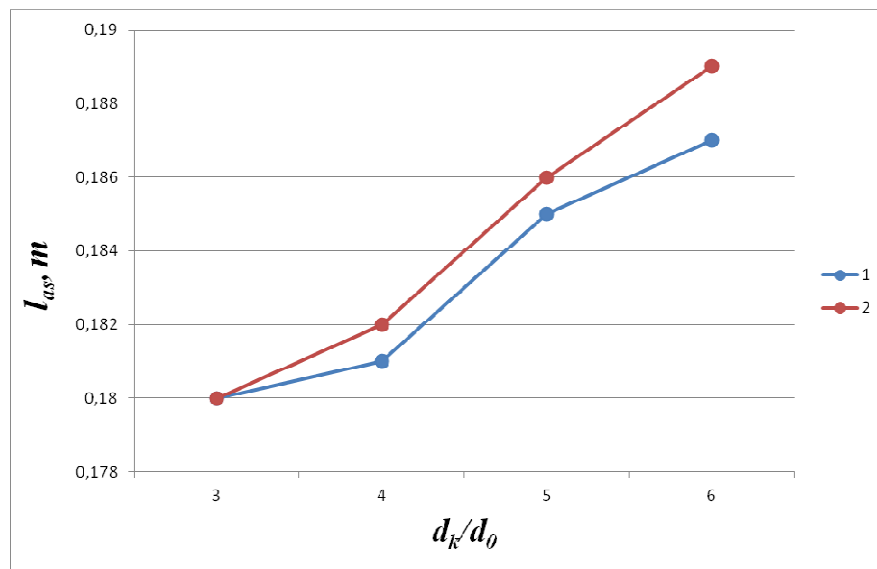

Figure 4. Effect of ratio $\dfrac{d_k}{d_0}$ on the length of the active section of the jet: 1 - $\mu = 0.6$; 2 - $\mu = 0.7$; $P_0 = 60$ Mpa; $d_0 = 0.0006$ m.
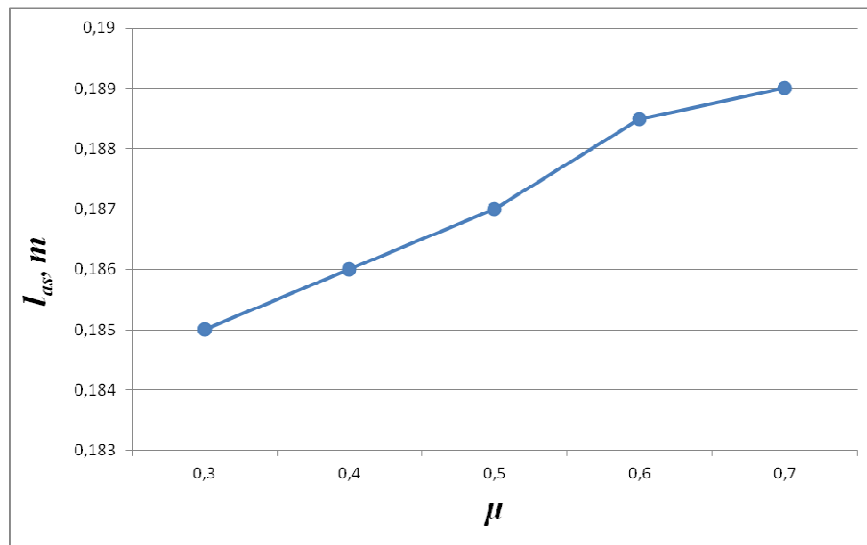
Figure 5. Effect of discharge coefficient μ of the jet-forming nozzle on the length of the active section of the jet: $P_0 = 60$ MPa; $d_0 = 0.0006$ m; $\dfrac{d_k}{d_0} = 6$.

The results were processed using a multiple regression method and the following final equation was obtained, which determines the effect of the pressure of high-pressure water P_0, the diameter of the jet-forming nozzle is d_0, ratio $\dfrac{d_k}{d_0}$ and the discharge coefficient of the jet-forming nozzle, μ, on the length of the active section of high-pressure water jet l_{as}:

$$l_{as} = 0.002 + 0.0021 P_0 + 61.84 d_0 + 0.003 \frac{d_c}{d_0} + 0.008 \mu, \qquad (7)$$

3. Conclusion

The analysis of the results of the conducted studies made it possible to determine that the water pressure increases simultaneously with the length of the active section of jet l_{as}. It was observed that the jet-forming nozzle of a larger diameter at a constant pressure would yield a larger length of the active section of jet l_{as}. Thus, with an increase in water pressure from 30 to 50 MPa, the length of the active section increases by 34% for all nozzle diameters. The increase in the nozzle diameter from 0.0003 to 0.0006 m at a constant pressure results in an increase of the active section of the jet length on average by 15.5%. The increase in l_{as} with rising P_0 and d_0 is directly proportional to the flow rate of high-pressure water. When the pressure increases, the rate of the jet outflow also increases. This increases the water carrying ability of the jet and more solid particles (ice) are carried into the flow therefore achieving a greater stability.

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