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Basis of high-pressure water-ice jet creation and application for surface treatment

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Abstract

The high-pressure water-ice jet treatment is a new technology that has grown in popularity lately. The presented technology is based on a high-pressure water-ice jet with addition of dry-ice CO_2 pellets. The theoretical basis, including velocity and kinetic energy distributions of ice particles also with thermodynamical particle states during the water-ice jet creation are discussed. Using theoretical results the experimental plant, accompanied with suitable equipment, was built. It enables adequate research to be achieved that makes it possible to determine the jet erosion mechanism and point out the effects of different material treatments.

1. Introduction

Surface treatment using the high-pressure water-ice jet consists in bulk micro-treatment the surface with ice particles transported with a water jet. Due to high rate of this jet, often aerated to considerable degree, the ice particles obtain the energy necessary to perform a treatment operation.

About 30 original scientific publications concerns that domain have been made all around the world recently [5]. A number of the surface processing technologies based on the use of the ice jet have been previously suggested. Another, the adoption of the ice jet technology is determined by the effectiveness of the generation and handling of ice jet abrasives.

A noticeable interest in high-pressure cryogenic jets, abrasive-cryogenic jets and ice jets has been aroused in recent years. A high-pressure ice jet is created by ice particles driven by a stream of air, other gas or water displaced with a great velocity. Ice particles applied to them are produced by freezing of water droplet [7] or by crushing the larger ice particles [9] or are obtained from dry-ice pellets [10]. Exactly this technology of ice generation has been wide spread lately. Usually dry-ice pellets are accelerated by compressed air [10]. Owing to that, components of this ice jet escape into the atmosphere leaving merely particles of disposable impurities.

It is possible to increase the efficiency of cleaning with a jet including dry-ice pellets, especially when fairly hard impurities are to be disposed of, making use of a high-pressure water-ice jet. Thus this paper is devoted to investigations on the physical basis of a high-pressure water-ice jet and application for surface treatment.

2. Theoretical basis

It is possible to assess the phenomena occurring in the process of surface treatment with the high-pressure cryogenic multiphase liquid jet and determine its physical principles analyzing the quantities describing dynamics of individual ice particles which is a spherical shape. Therefore, the present theoretical analysis of ice particles behavior during their acceleration and interaction with the material was designed for such the sprinkler with a concentric nozzle [3]. The ice grain kinetics in the high-pressure water jet and their thermodynamic state analyses that decide of the ice grain quality as an erosive particle are required.

2.1. Kinetics of high-pressure water-ice jet

In order to create the high-pressure water-ice jet with high-quality erosion properties it is necessary to know the ice grain abrasive material behaviour. Therefore it is important to know ice particles velocity in the sprinkler outlet, especially in the erosion area and its kinetic energy.

2.1.1. Velocity of ice particles

Theory supported on fluid mechanics laws was used to determine the length of ice-grain acceleration. Under steady-state conditions of fluid flow, the thrust force of a jet counterbalances the aerodynamic resistance of ice particles causing its acceleration. On that basis [4, 5] it is possible to establish expression describing the ice-grain velocity in the erosion area:

$$v = \left(\frac{u^2 t}{ut + K} \right) \cdot \left(\frac{D_o}{D} \right)^2 \eta , \tag{1}$$

where: K – constant $K=(8r\rho_i):(3C_D\rho_w)$,
C_D – drag coefficient of ice particles moving in a water jet,
ρ_i, ρ_w – medium (ice, jet) density,
t – time,
u – high-pressure multiphase water jet velocity,
v – ice-grain velocity in a stream,
r – radius of a model spherical ice-grain.
D – jet diameter at a cross-section under consideration,
D_o – jet diameter at a sprinkler outlet,
η – coefficient of jet efficiency.

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It is possible to determine quantities D, D_o, η included in these formulas only by the experimental method [5]. Considering the above relationship (1) the appropriate calculations of the highpressure water jet flow-velocity in a zone of collision with the workpiece were carried out. Example results of flow-velocity calculations for crushed ice particles in the erosion area 250 mm distant from the sprinkler tube outlet ($v_{0.25}$) are presented in Fig. 1a and for dry-ice pellets - in the erosion area 500 mm distant from the sprinkler tube outlet ($v_{0.5}$) - are presented in Fig. 1b. It is evident that an increase in the sprinkler tube length and the rated water pressure causes an increase in the ice-grain velocity.

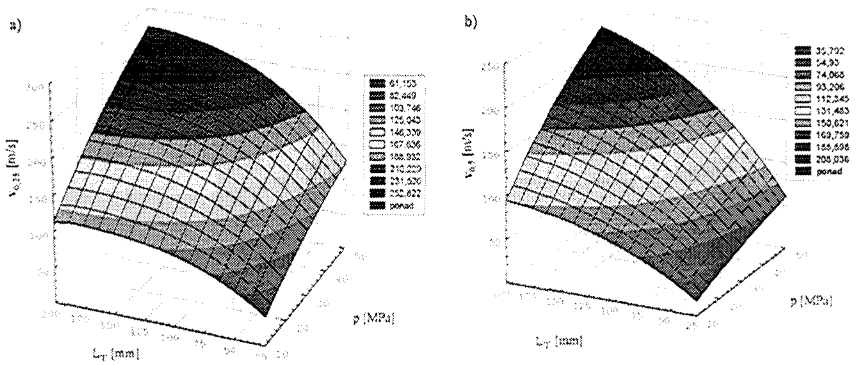

Figure 1: Influence of the sprinkler tube length and water pressure on the velocity in the erosion area for ice particles moving in jet of 30% water content. a) crushed ice H_2O (r =0,75mm), b) dry-ice CO_2 (r =1,55mm).

A crucial practical conclusion was drawn from these investigations that the ice-grain velocity both at the sprinkler tube outlet and the erosion area only to slight extent depend on intensity of water-jet aeration. Highpressure water-ice jet created in the cryo-sprinkler with the concentric nozzle [3] inside is hardly sensitive for jet aeration. The ice-grain velocity in the sprinkler tube outlet is comparable high in a wide range from 100 % to 30 – 40 % of water content in highpressure liquid jet. Therefore it is advisable for water-ice jet creation to use the short tube sprinkler (with the length L_T = 100÷150 mm).

2.1.2. Kinetic energy of ice particles

Making use of the above specified ice-grain flow-velocity it is possible to calculate their kinetic energy E_K in the cutting zone as well, according to the following expression:

$$E_K = \frac{2}{3}\pi r^3 \rho_i v^2 . \tag{2}$$

Diagrams of kinetic energy for crushed ice particles in the erosion area 250 mm distant from the sprinkler tube outlet ($v_{0.25}$) are presented in Fig. 2a and for dry-ice pellets - in the erosion area 500 mm distant from the sprinkler tube outlet

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($v_{0,5}$) - are presented in Fig. 2b. As shown in the illustrations, an increase in the sprinkler tube length and water content in a jet aerated and the water pressure causes an intensive increase in the kinetic energy of ice particles. The above results revealed that, for different dimension of crushed ice and dry-ice pellets and consequently their different density, the kinetic energy of dry ice pellets is 8,5÷10 times higher than the crushed ice particles.

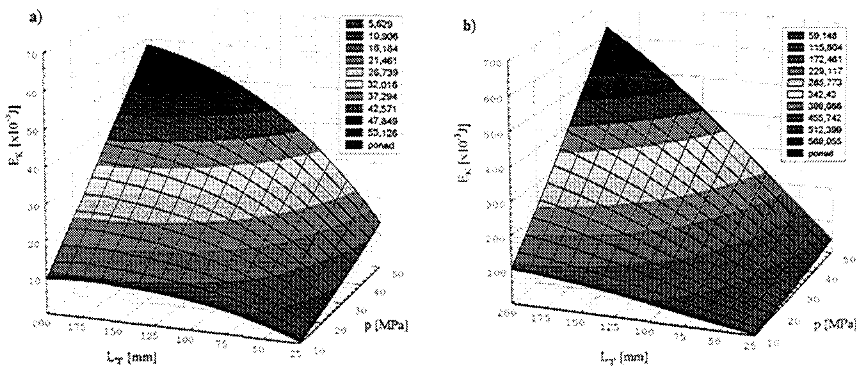

Figure 2: Influence of the sprinkler tube length and the water pressure on the kinetic energy for ice particles carried by jet of 30% water content, a) crushed ice H_2O (r =0,75mm), b) dry-ice CO_2 (r =1,55mm).

2.2. Thermodynamics of ice particles

To evaluate the suitability of ice particles for cleaning one has first of all to get to know a temperature which will have they at respective stages of the process creating the water-ice jets. A model of a thermal transient conduction in a system of weak thermal resistance was used to determine a temperature of ice particles.

To obtain an equation allowing calculating the end temperature of ice particles, on the basis of well known Newton's heat equation, the energy balance should be drawn up. After transformation of the energy balance and calculation of end temperature of ice particles after "heating up" by air during its transport from a container to a sprinkler and with highpressure water jet, it is possible to determine [2, 6] the following equation:

$$T_{ie} = T_w - \left[\left(T_w - T_a\right) + \left(T_a - T_i\right) \cdot e^{\frac{-\alpha S}{c\rho V} t} \right] \cdot e^{\frac{-\alpha S}{c\rho V} t} \tag{3}$$

where: c – specific heat of ice,
α - coefficient of heat absorption,
ρ - ice density,
S – surface of ice-grain,
T_l – liquid temerature (air T_a or water T_w),
T_i – initial ice temperature,
V – volume of ice grain.

Taking this equations (3) into consideration a series of calculation of ice particles therodynamical states were made which enable to determine suitability of ice particles in the process of cleaning as it is shown on exemplary Figures 3 and 4.

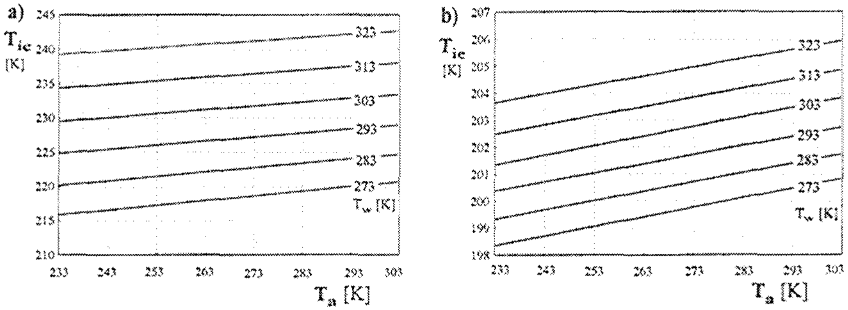

Figure 3: The end temperature of ice vs. temperature of air used for transport of ice particles for different temperature of water jet: a) crushed ice H_2O (r=0,75mm), b) dry-ice CO_2 (r=1,55mm). Water pressure p = 20 MPa, length of suction hose l_1=5 m, initial temperature of ice T_i = 193 K, distance between water ice jet outlet from sprinkler tube and work material l_2 = 250 mm.

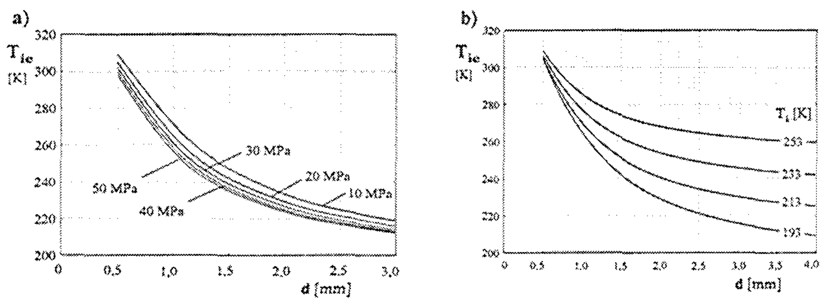

Figure 4: The end temperature of ice vs. ice particle diameter for different water pressure (a), initial temperature of ice (b). Air temperature of T_a = 293 K and water temperature of T_w = 323 K, p = 20 MPa, T_i = 193 K, l_1 = 5 m, l_2 = 250 mm.

On the basis of above graphs analyses one can state that the initial temperature of ice grain is a factor strongest affecting the end temperature of ice grain. The next factor regarding their intensive influence on the end temperature of ice grain is their size and a distance between a water-ice jet outlet form a sprinkler tube and the work material. A slighter influence on the end temperature exerts a temperature of water and the next after is water pressure which has the effect on a jet rate and therefore its time of "heating up" of ice particles. A temperature of air has a little influence on the end temperature of ice and the slightest effects exerts the suction pipe length. All that is essential for appropriate construction of the necessary experimental plant.

3. Experimental plant and equipment

Taking into consideration above theoretical analysis results it was build the suitable experimental plant, exemplified by Fig. 5, is to be applied. This plant includes a valve 1 supplying municipal water to a cooler 2 (Fig. 6a) where it is pre-cooled. A high pressure pump 3 (Fig. 6b) enables to obtain a water jet at adequate pressure which is stabilized by a control system 4. This jet is once again cooled in a cooler 5 than it flows to a high pressure spray gun 6 (Fig. 6c) and a cryo-sprinkler 7. This sprinkler is different in design from the previous one [3] mainly due to characteristics of the concentric nozzle and external and internal insulating inserts. A high pressure water jet flowing through a cyro-sprinkler 7 produces a negative pressure in a tube 9 sucking in ice particles from a container 10 situated in a room at a controlled temperature. Ice particles sucked up from a container 10 to a nozzle of a cryo-sprinkler 7 get accelerated by a high pressure water jet and formed in a water-ice jet sprayed on a workpiece 8. Earlier experiments [1, 5] let to establish that the best building of cryo-sprinkler is equipped

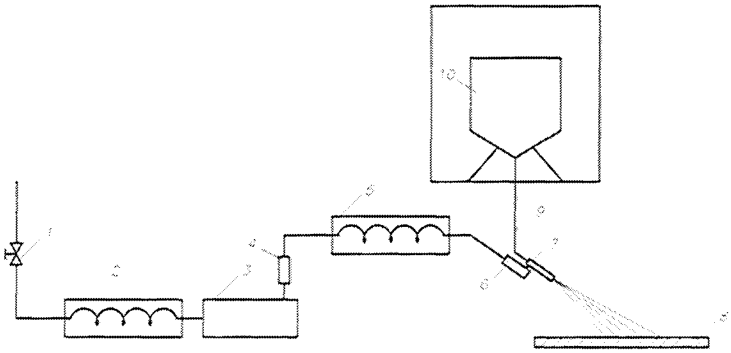

Figure 5: Sample test-stand for creation highpressure water-ice jet.

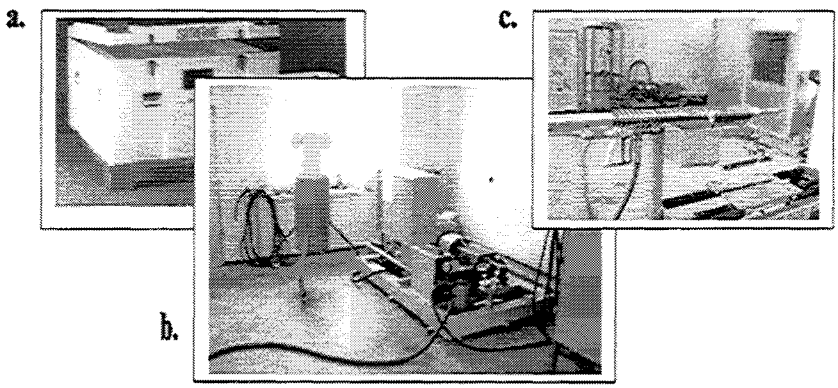

Figure 6: Equipment and a test stand: a – water cooler, b – hydromonitor with a highpressure pump and a control system and a dry-ice pellets hopper, c – test stand with a highpressure spray gun and a cryo-sprinkler.

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with a four-outlet concentric nozzle with water jets d_w=1.2mm in diameter and a tube D_T=22 mm in diameter and L_T= 150 mm in length.

The high-pressure water-ice jet configured in this way was used for processing about a dozen different types of material such as metal plates (steel, aluminum, copper and lead), plastics, PVC materials, plexiglass, glass, ceramics, different rock materials, rubber etc. Surfaces of the above materials differed in quality because apart from their natural state they had surfaces passivated, corroded and also coated with paint or asphalt (izohan type), either rubberized or glue spread etc. Lead, which is distinguished by high ductility, was most often used for testing the course of erosion mechanism with this sort of water-ice jet.

Quality and a degree of surface erosion of processed materials were assessed with different measuring instruments, including:

- scanning electron microscope JEOL 5500LV,
- TalyScan 150 Dual Gauge System of Taylor-Hobson.

4. Effects of surface treatment

From among different effects of surface treatment observed during the studies only mechanisms of cleaning process and also conditions and efficiency for different materials are discussed here.

4.1. Mechanisms of surface treatment

It is evident that if the highpressure water-ice jet is used for cleaning, the main mechanism of surface treatment consists in hydrodynamic impact of ice particles and water on the material as it was being removed. The most characteristic feature of the highpressure cryogenic liquid jet affecting the work surface reliance on multiple impingements of jet droplets, together with ice particles transported, against the work surface result in formation of quick-variable stresses. A fatigue character of these variables contributes to the surface cracking, usually dispersing in different directions [4].

However, the mechanism of material removing from surfaces with the highpressure water jet with dry-ice pellets is very complicated. The most decisive effects on the intensity of this process produce the dry-ice (CO_2) pellets forming effective tool-points attacking on the work surface with great energy. Dry-ice pellets CO_2 particles, crumbled down during surface treatment impact, penetrates under the dirt layer, and then sublimates enlarging of approximately 800 times of its volume. Sudden character of that process is nearly explosive, while the treatment zone is smoggy caused of condensate CO_2 gas. Water plays also important part in this process revealing its effects not only in the form of cavitational erosion, but also as a medium penetrating the cracks obtained, causing disaggregation of the material. This mechanism generally results in uniform spalling of particles splitted off the workpiece surface.

Dry-ice pellets behave in the way similar to abrasive grains. That kind behavior is shown in SEM micrographs (Fig. 7) of treated surface with highenergy hybrid jet comprising ice particles and abrasive grains. However, it

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stands to reason that impact of ice particles is significantly mild than abrasive grains.

Analyses of mechanisms of surface treatment with a highpressure water-ice jet also conformed occurrence of distinctly wavy characteristics of erosion. It is illustrated in photographs presented in Fig. 8. However these investigations did not confirmed the essential effect of cryogenic shrinkage of coatings, which could intensify the decoating process.

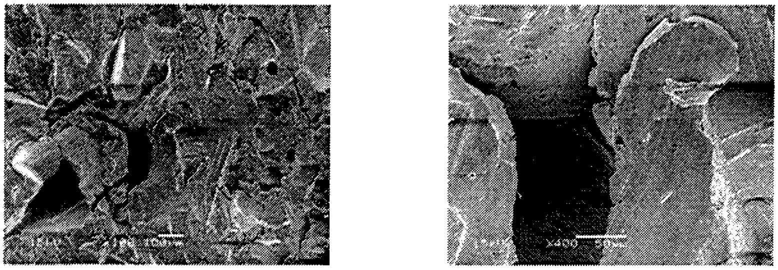

Figure 7: Surface treated by highenergy hybrid jet with exposed loosened chips of eroded lead material.

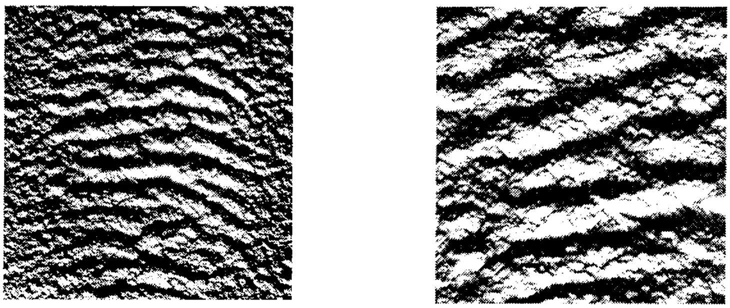

Figure 8: Example of the surface (lead) after treatment by highpressure water-ice jet, showing a wavy character of erosion.

4.2. Condition and efficiency of cleaning process

A highpressure water-ice jet is formed of a few water jets discharged from outlet of a concentric nozzle [3, 5]. A concurrent flow of these water jets through a sprinkler tube causes the central outlet of the concentric nozzle to suck in air along with ice particles. The water-ice jet obtained in this way has fairly homogeneous structure and while discharging from the sprinkler tube impacts on the treated surface with high energy.

Consumption of water and dry-ice pellets during the trade off studies concerned with cleaning the corroded surfaces of steel plates using the water-ice jet ranged from 40 to 55 dm^3/min of water and from 2.3 to 2.8 kg/min for ice pellets respectively, that equals the flow intensity of about 1500÷2000 dry-ice pellets per second. It ensured satisfactory surface processing for these plates with

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maximum efficiency from 0.35 to 0.45 m^2/h. In comparison, the ice consumption while accelerating the ice particles with compressed air in various experimental conditions ranged from 0.4 to 1.1 kg/min, however the efficiency of processing was less than six times lower [8].

A highpressure water-ice jet regarding its more favourable process conditions was used for cleaning the surfaces of various materials. Results of these experiments are related to efficiency of cleaning, quality of surface treatment and effectiveness of cleaning. They were worked out as relative values, classifying the results as follows: ++ very good, + good, * satisfactory, - improper. The results of preliminary tests on cleaning chosen material, compiled in this way, are presented in Table 1.

Table 1. Relative efficiency of cleaning the surfaces of chosen material

treated material types	coatings types	cleaning effectiveness	quality of cleaned surface	cleaning efficiency
steel plate	surface corrosion	*	+	-
	deep corrosion	+	+	*
	mixed corrosion	*	+	-
	asphalt type izohan	*	*	-
	paint	+	*	*
	rubber glue	+	*	-
	epoxide resin	*	-	*
aluminum plate	asphalt type izohan	*	*	*
	paint	+	+	+
	rubber glue	+	*	*
	epoxide resin	*	-	*
plastics	asphalt type izohan	*	-	*
	paint	+	+	+
	rubber glue	+	-	*
	plasic glue	*	-	*
	epoxide resin	+	*	*
glass	asphalt type izohan	+	*	+
	paint	+	++	++
	rubber glue	+	+	+
	plasic glue	+	+	+
	epoxide resin	+	+	*

A highpressure water-ice jet regarding its more favourable process conditions was used for cleaning the surfaces of various materials. Results of these experiments point out that the most efficient is varnish coatings cleaning of the glass and steel sheet, especially lead surfaces. Also good effects are for cleaning such a surfaces of different plastic and rubber glues layers (coatings).

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5. Conclusions

• Effectiveness of surface treatment with a highpressure water-ice jet depends on the quality of ice particles. For this reason it is recommended to use the ice of the highest quality and also possibly the lowest temperature of a highpressure water jet so that the quality of ice particles accelerated with it declined as low as possible.
• The dominant mechanism of output while cleaning with a highpressure water-ice jet is a hydrodynamic impact of ice particles on the material producing the distinctly wavy characteristics of erosion.
• Satisfactory effects of cleaning the surface with highpressure water-ice jet were obtained at the temperature of water not exceeding 15^0C, at the pressure p=30 MPa and its consumption Q_w=40÷55 dm^3/min and dry-ice consumption Q_i=2.3÷2.8 kg/min. Under these circumstances the rate of cleaning the corroded steel plates can reach 0.35÷0.45 m^2/h, which is almost six times more efficient than cleaning with a ice jet brought up to speed by compressed air.
• In order to increase the efficiency of surface treatment with a highpressure water-ice jet one should have the following in view: increased overcooling of ice which is characterised by more favourable morphology of ice; using the cryogenic jet of driving fluid, which is supposed to produce an additional thermal shock in the material subject to removal; using the high-pressure hybrid jet comprising apart from ice particles also grains of proper abrasive material.

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