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Study of the efficiency of cavitation generating head with water removal system used to remove foulants from metal surface

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Abstract. The paper presents a novel, environment-friendly method for removal of foulants from surfaces. Various adhered foulants as solid particles and the like can be detached from surface by cavitating pulsating water jet which is generated in specially designed nozzles and directed on the surface being cleaned. The objectives of this research were to establish fouling removal efficiency of developed cavitation generating head and residual water removal efficiency of its cyclone-type water removal system which is used to remove water residuals from cleaned surface. It was experimentally established that 100% abrasive particle removal efficiency from metal surface is achieved when distance between head outlet and surface is varied from 1 to 8 mm. The most effective is cavitation generating head with water removal system in which the flow is drawn in the same direction as the air flow is supplied inside the head. If this water removal system is used, the average visible water content on the metal surface equals to 1.4%, while when the flow directions are opposite, water content is increased to 27.2%.

Keywords: Abrasive particles / water / cavitation / surface being cleaned / nozzle / removal efficiency

1 Introduction

In contemporary production systems, with the diminution of dimensions of manufactured parts, the quality requirements for surface preparation are also tightened. Often the desired level of surface cleanliness is achieved by means of toxic solvents, freons, surfactants, but tightening environmental requirements complicate use of conventional surface preparation methods [1].

During the manufacturing process, layers of undesirable materials are formed on the surfaces of the products, their surfaces are often fouled. Surfaces may be fouled with residues of materials used in the treatment process or by airborne particles in production sites. Surface fouling can be divided into fouling by films and fouling by solid particles [2].

Depending on the production process, different requirements are raised for the preparation of surfaces. Therefore, it may be necessary to remove various layers from the surface starting from the adhesion layer and ending to the chemical reaction layer. The closer the removal layer to the base material, the greater amount of energy must be applied to remove this layer, which is very important to choose a suitable method for cleaning the surface. Parts cleaning methods can be classified as follows [3]:
– Solvent cleaning,
– Aqueous cleaning,
– Mechanical cleaning,
– Precision cleaning,
– Ultrasonic cleaning.

Cleaning methods must not only meet the increasing requirements to the level of cleanliness of the surface, but must be as less as possible harmful to the environment. An effective fouling removal method is the use of chemicals as it allows to achieve up to 100% fouling removal but with the negative environmental impact due to the release of chemicals after use, as well as with down-time of the facility [4]. Other methods like precision cleaning require very complex and expensive equipment. Therefore, scientists and engineers are constantly looking for more efficient and environmentally friendly fouling removal processes.

One promising method of fouling removal is the use of ultrasound [4]. Its origins date back to the 1950 s and it was beginning to become established around 45 years ago [5,6]. Ultrasonic cleaning is widely employed in various manufacturing and maintenance processes, including optical surface cleaning, semiconductor manufacturing and machinery maintenance [7]. Currently, ultrasonic cleaning is

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becoming more and more widespread for the cleaning of dental and medical instruments [5,6]. The cavitation caused by ultrasound is the main reason for cleaning.

Cavitation is a process known for its deleterious effects such as noise, material erosion, and loss of performance [8]. It begins when the local pressure in the liquid drops below a saturated vapor pressure due high accelerations and velocities of the liquid and this turns microbubbles (cavitation nuclei) present in liquid to grow abruptly [9–11]. When pressure along the trajectory of bubbles returns to a high value, medium implosions occur, which result in shock waves and high-pressure pulses [12]. Dynamic motion of formed bubbles in response to acoustic waves creates forces, which remove fouling adhered to surface and produce cleaning effect [7,13]. Scientists assign removal effects to different dynamic actions of cavitation bubbles, for instance, microstreaming caused by pulsating bubbles, high-speed jets and shock waves upon bubble collapse and interfacial collisions of moving bubbles [7]. Conventionally, ultrasonic baths are used to clean individual components by generating cavitation bubbles that implode on the surface being cleaned [4]. Parts that have accumulated contaminants are immersed into ultrasonic bath [4]. Ultrasonic cleaning can be used for both large and small components and can penetrate deep into cavities of the surface being cleaned [5]. It is generally considered to be non-toxic, safe and environmentally friendly as works well with aqueous solvents that displaced the more hazardous halocarbons [5].

Since in the ultrasonic cleaning process fouling removal takes place due to cavitation, it is possible to formulate the hypothesis that the surface can also be cleaned by the cavitating water jet. The use of cavitation generating nozzles for the cleaning of surfaces solves the main disadvantage of the ultrasonic cleaning method: there is no need to immerse cleaned parts in the ultrasonic bath, this reduces cleaning process time and costs.

When cleaning surfaces by cavitating water jet, only water is used, which flows through nozzles responsible for the cavitation process. Therefore, no additional chemical solvents are used in the cleaning process that could pose any risk to the environment or human health. Also, the water used in the process can be reused after cleaning it from contaminants that were removed from the surfaces. This minimizes emissions.

However, high supplied water pressure is required to induce cavitation in the jet flowing through the nozzle. It is usually between 80 and 150 bars [14]. In order to cause cavitation at a lower pressure, specially designed nozzles are used, in which the flow pulsates as it swirls [15,16]. Pulsations caused by the eddies of the water flow act as sound waves in the ultrasonic cleaning process. Therefore, by applying a swirling pulsating flow, cavitation process can be induced already at water pressure of 30 bar. The development of this method began with the use of cavitation generating nozzles for surface processing, for example, drilling [17,18] or polishing [19]. Cavitating jets use the energy emitted by bubbles collapse to increase impact force [14].

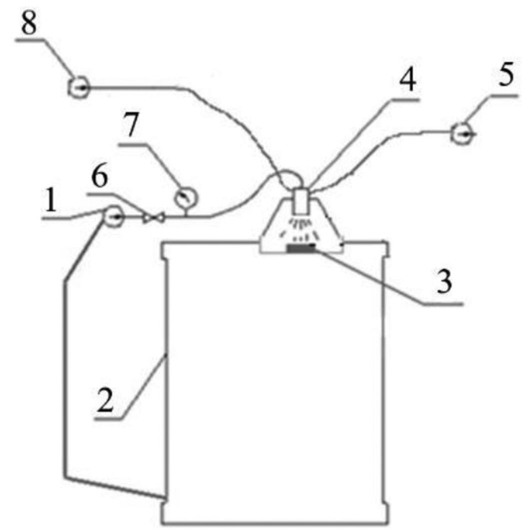

Fig. 1. Scheme of surface cleaning using cavitating water jet: 1–water pump (flow rate 18 l/min, max. pressure 140 bar); 2–water tank; 3–surface being cleaned; 4–cavitation generating head; 5–vacuum pump (flow rate 240 l/min); 6–valve; 7–pressure gauge; 8–air blower (flow rate 150 l/min, pressure 1 bar).

2 Materials and methods

A prototype of a cavitation generating head and an experimental stand were made for experimental studies of aluminum surface cleaning from stuck abrasive particles. Scheme of experimental stand is presented in Figure 1.

Experimental stand was designed with the ability to collect and reuse water used to clean surface 3 (Fig. 1). Water is supplied to the cavitation generating head 4 from tank 2 by water pump 1. A pressure gauge 7 is used to control water pressure. A blower 8 is used to supply air to the cavitation generating head 4, which is used to remove water and contaminants from the cleaning area. Vacuum effect 5 is added to the top of the head 4 to enhance water removal efficiency.

Single cavitation generating nozzle directed to the surface being cleaned would also be suitable for surface cleaning, but previous research [20] showed that traces of water remain on the cleaned surface, which reduce the efficiency of the proposed method. Therefore, there was a need to design a system (head) with water removal system. The scheme, 3D model and image of this cavitation generating head are presented in Figures 2–4 correspondingly.

Head consists of three cavitation generating nozzles (atomizers) NECBD [15,20,21] arranged at 120° angle with respect to each other (Figs. 2 and 3, view I). The water supplied by the pump to the head housing enters the annular channel, then to the nozzles as it is shown in Figure 3. Nozzles whose angular position in relation to the axis of the head can be changed, generate cavitation and direct the flows on the surface being cleaned. The results of numerical investigations of cavitation generating efficiency of nozzles are presented in [20,21].

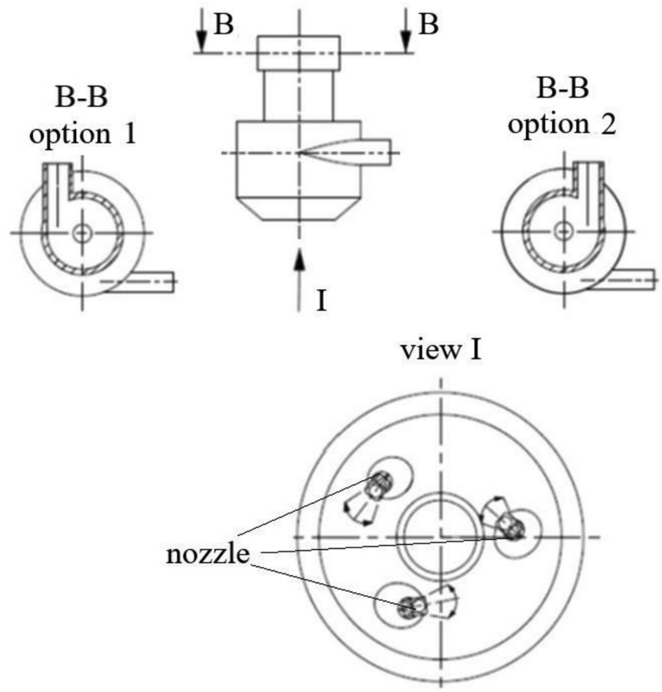

Fig. 2. Drawing of cavitation generating head with water removal system.

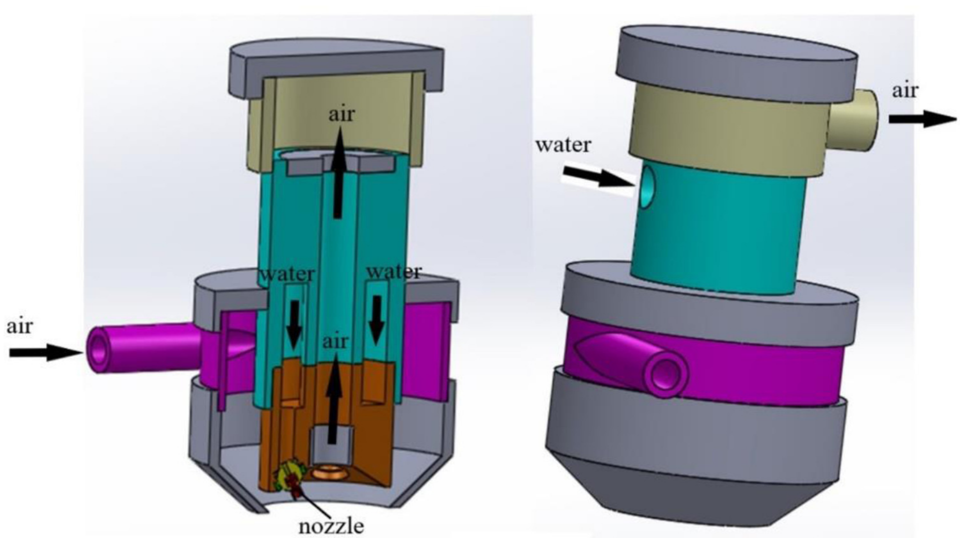

Fig. 3. 3D model of cavitation generating head with water removal system.

Water removal system works similarly as conventional cyclone separator. Air from blower is tangentially supplied to the head (Figs. 3 and 4), where the vortex is created. The rotating air flow generates pulling force which catches the removed contaminants and water from the surface being cleaned and takes out them through the center part of the head. To increase removal efficiency of the head, the vacuum effect is added to the top of the head.

Fouling removal efficiency of the head was studied experimentally by means of experimental stand presented in Figure 1. For that the aluminum plates were ground by flat grinding machine by means of abrasive wheel made from white aluminum oxide (its coarseness was 250–400, bonding material – ceramics, medium soft wheel). Next, stuck in aluminum surface abrasive particles were analyzed by digital microscope and their positions were registered. Then ground surface was placed under the cavitation generating head and processed with cavitating water flow within one-minute time interval (for each particle). Then plate was analyzed by microscope again. Microscope images before and after the processing with cavitating water jet were compared by means of computer in purpose to establish the absence of particle in aluminum surface. Each experiment was performed with five stuck abrasive

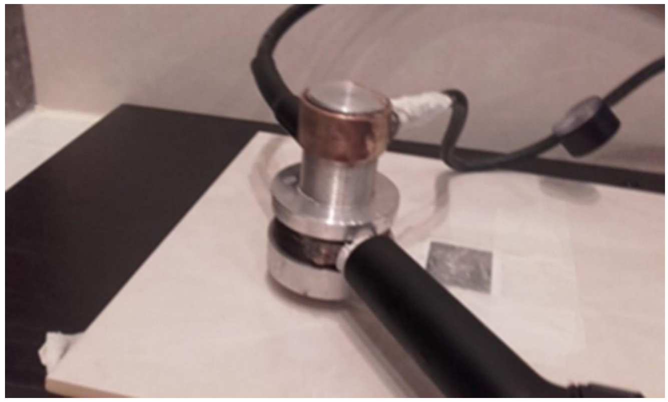

Fig. 4. Image of cavitation generating head with water removal system.

particles and percentage particle removal efficiency values were calculated.

The following water pressure was used in experiments: 4 MPa. The distance between head outlet and surface was varied from 1 to 160 mm.

Experimental investigations of water removal efficiency of cavitation generating head with water removal system were carried out with two variants of air extraction system (Fig. 2, section B-B): option 1–the flow is drawn out in the same direction as the air is supplied to the head; option 2–the flow is drawn out in the opposite direction to the direction of supplied air flow.

To evaluate efficiency of proposed water removal system, 40 layered aluminum foil wafers with a thickness of 3 mm were prepared for experiments. The specimens were mounted on a ceramic plate and their surface images were taken by microscope. Then specimens were placed under the cavitation generating head and processed by cavitating water jet for 1 minute. 20 tests (a total number of tests is 40) were performed with each cavitation generating head option. 4 MPa water pressure and 0.1 MPa air pressure were applied in experiments and the vacuum pump was used for its maximum flow rate 240 l/min. After the test, the specimens were placed under microscope again and digital surface images were made again.

To establish the amount of water remaining on the surface, a virtual grid was placed on an image and the surface area covered with water was calculated.

The Solid Works Flow Simulation software was used to simulate a cavitation process in the cavitation generating head. An Engineering Cavitation model was used in this study. This model employs a homogeneous equilibrium approach and is available for pre-defined water only. It has the capability to account for the thermal effects. The fluid is assumed to be a homogeneous gas and liquid mixture with the gaseous phase consisting of the vapor and non-condensable (dissolved) gas. The vapor mass fraction is defined at the local equilibrium thermodynamic conditions. The dissolved gas mass fraction is a constant, which can be modified by user. The velocities and temperatures of the gaseous (including vapor and non-condensable gas) and liquid phases are assumed to be the same.

Initial and boundary simulation conditions are presented in Table 1.

3 Results and discussion

Results of experimental study of aluminum oxide particles removal efficiency are presented in Figure 5. It can be seen in Figure 5 that cleaning efficiency decreases as the distance from head to the surface to be cleaned increases. It can be seen from Figure 5 that maximum 100% removal efficiency is achieved when distance is varied from 1 to 8 mm. A minimum removal efficiency of 20% is achieved when the distance is maximum i.e., 160 mm.

Results of experimental study of water removal efficiency are presented in Table 2. Some examples of microscope images of foil surfaces before and after processing by cavitating water jet are presented in Figure 6. Microscope image of surface with the grid is presented in Figure 7.

Experimental results (Tab. 2) show that the water is more efficiently removed from the surface when the cavitation generating head with water removal system of 1st type (in which the flow is drawn in the same direction as the air is supplied, Fig. 2, section B-B, option 1) is used. It was established that in this case the average visible water content on the surface is 1.4% only. In case when the head with water removal system of 2nd type (Fig. 2, section B-B, option 2) is used, water amount equals to 27.2%.

Obtained difference in water removal efficiency can be explained by the fact that the vortex created by air flow supplied to the cavitation generating head with system of 1st type is additionally amplified by the exhaust air flow creating a greater pulling force than in case of the head with water removal system of 2nd type.

The right part of Figure 8 presents the distribution of vapor fraction on the cleaned surface obtained during the numerical simulation using SolidWorks Flow Simulation software. It can be seen from Figure 8 that there are zones on the surface where the proportion of vapor exceeds 80%, which indicates that intensive cavitation zones are formed on the surface.

Table 1. Initial and boundary conditions used in the numerical simulation of cavitation process.

Initial conditions	
Velocity parameters	Velocity vector components: Velocity in the direction of X axis: 0 m/s Velocity in the direction of Y axis: 0 m/s Velocity in the direction of Z axis: 0 m/s
Thermodynamic parameters	Static pressure: 101325.0 Pa Temperature: 293.20 K
Water supply parameters	
Surface	Cross-sections of the nozzle outlet (Fig. 3)
Parameters of the flow	Flow vector direction: normal to the surface Water flow pressure: 4000000.0 Pa
Turbulence parameters	Turbulence intensity: 2.00% Turbulence length: 0.003 m
Parameters of the boundary layer	Type: Turbulent
Flow extraction parameters	
Surface	Cross-section of the outlet (Fig. 3)
Parameters of the flow	Flow vector direction: normal to the surface Flow rate: 0.004 m^3/s
Turbulence parameters	Turbulence intensity: 2.00% Turbulence length: 0.003 m
Parameters of the boundary layer	Type: Turbulent
Air supply parameters	
Surface	Cross-section of the air inlet (Fig. 3)
Parameters of the flow	Flow vector direction: normal to the surface Pressure: 101275.07 Pa
Turbulence parameters	Turbulence intensity: 2.00% Turbulence length: 0.003 m
Parameters of the boundary layer	Type: Turbulent

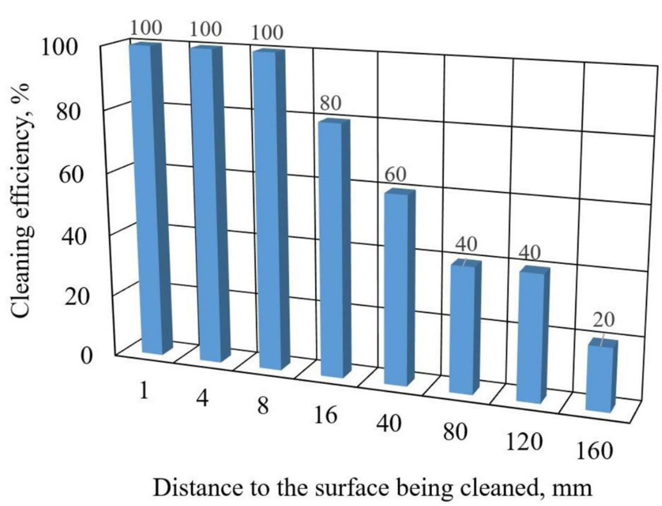

Fig. 5. Aluminum surface cleaning efficiency versus distance between end of the head and surface being cleaned.

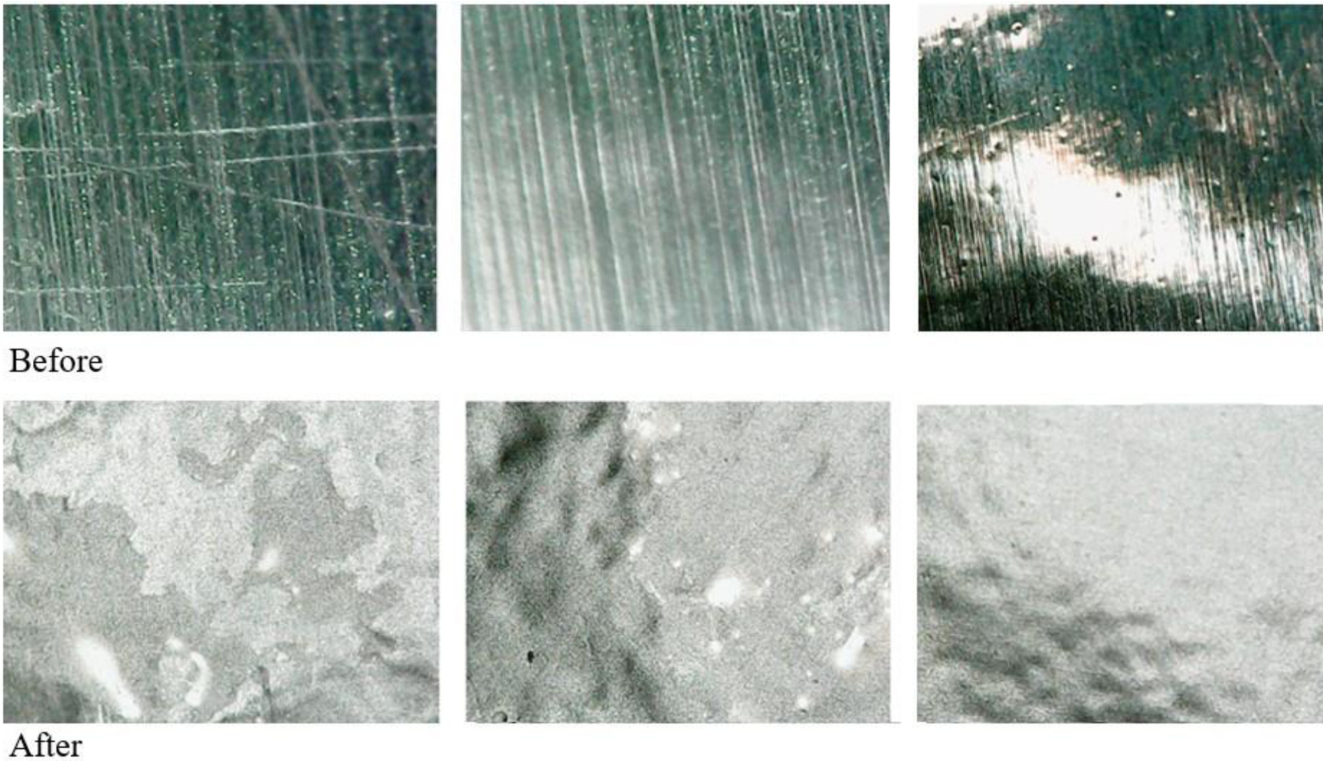

Fig. 6. Foil surface images before and after processing.

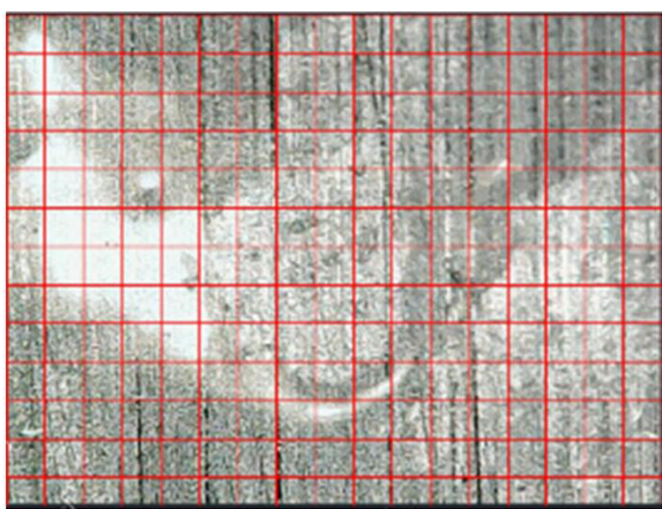

Fig. 7. Foil surface image with digital grid.

Table 2. Statistical results of the experimental data.

Design of the cavitation generating head	Number of measurements	Minimum amount of water remaining on the surface, %	Maximum amount of water remaining on the surface, %	Arithmetic mean, %
Option 1 (Fig. 2)	20	0.4	2.5	1.4
Option 2 (Fig. 2)	20	24.4	32.0	27.2

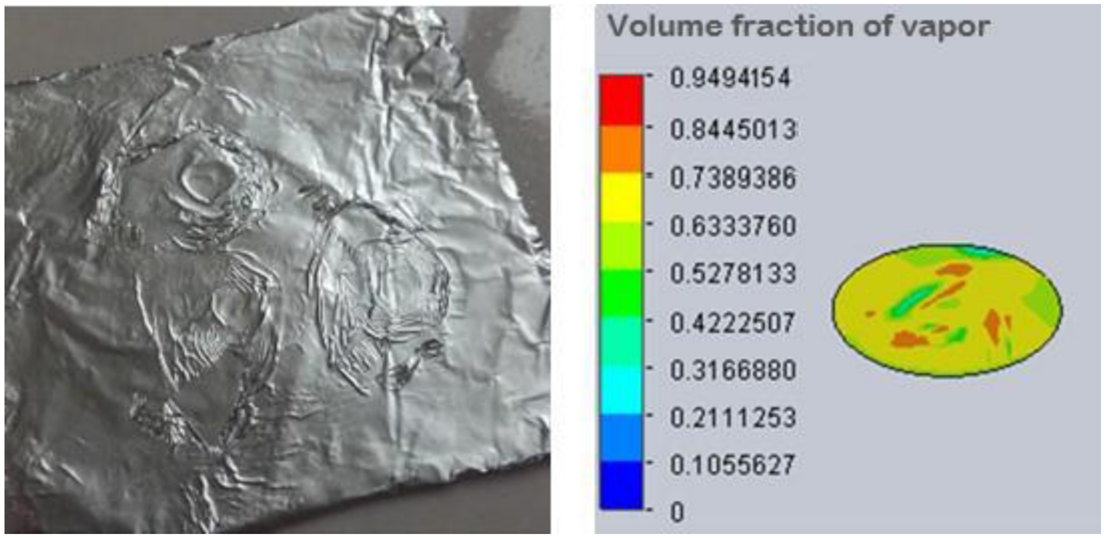

Fig. 8. Comparison of experimental and numerical simulation results.

Table 3. Results of numerical simulation of cavitation process.

Name of the parameter	Value	
	Minimum	Maximum
Pressure, Pa	1329.83	21100000
Temperature, K	280.78	303.07
Velocity, m/s	0	483.243
Velocity component along the X axis, m/s	–313.584	310.952
Velocity component along the Y axis, m/s	–387.125	292.817
Velocity component along the Z axis, m/s	–271.435	37.371
Volume fraction of vapour	0	0.949
Mach number	0	118.06
Density, kg/m^3	9.81	1017.36
Shear stresses, Pa	0	40793.17

Comparing the areas of the surface affected by cavitation (Fig. 8, left) and distribution of cavitation clouds obtained during the numerical simulation (Fig. 8, right), it can be seen that location of the areas affected by cavitation coincide with numerical simulation results.

Other numerical simulation results are presented in Table 3.

4 Conclusions

A novel non-reagent, environment-friendly method for cleaning surfaces from fouling is proposed. To remove foulants, cavitating water jet generated in cavitation generating nozzle is directed on the surface being cleaned.

A prototype of cavitation generating head with three nozzles and water removal system of two types was developed, manufactured and studied.

It was established that 100% abrasive particle removal efficiency is achieved at small distances between head exit and surface being cleaned, i.e., 1–8 mm. As the distance is further increased, removal efficiency decreases.

Experimental results have shown that water is more efficiently removed from the surface in case of use of cavitation generating head with water removal system in which the flow is drawn in the same direction as the air flow is supplied. It was established that the average visible water content on the surface equals to 1.4% in this case, while when the flow directions are opposite, water content is increased to 27.2%.

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