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LIQUID ENERGY ANALYSIS FOR THE SPRAY NOZZLE JET PARAMETERS OPTIMISATION

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Abstract: In the paper numerical analysis of the liquid energy regarding the spray nozzle jet parameters optimisation for a cleaning process has been presented. Special attention has been paid to the comparison between the energy contained in the stream of liquid going out from a nozzle, and the energy needed to remove fouling from the surface. In the example a lot of parameters influencing those energies have been taken into account. It has been found that the proposed analysis of the liquid energy and the energy needed for cleaning is an adequate description of geometry and parameters of equipment and devices, especially in the Clean In Point (CIP) systems.

Keywords: liquid jet energy, process optimisation, food industry

1. Introduction

Spray nozzles as parts of different equipment have many industrial applications. Among others they are mainly used for distribution and orientation of liquid stream in combustion chamber of energetic boilers or engines. They are also a basic part of a variety of cleaning systems. The latter application has recently been strongly developed as far as the energy of liquid and the spray nozzle parameters with respect to the cleaning procedure are concerned. This problem is extremely important in industries, where the highest possible hygienic standards are to be achieved. Furthermore, it is pertinent to say that from the economic point of view, cleaning is an operation that produces costs only. In spite of that, the most important fact should be taken into consideration, that it is impossibile to achieve high quality products if cleaning is not done properly.

The design of reliable and efficient cleaning system is a difficult task, especially for food industry (Brash 1985, Corradini 1985), where removing different fouling from equipment, and keeping its sufficiently high performance. Early studies (Jackson 1982, Plett 1984, 1985, Tissier 1984) revealed that the basic criteria to define cleanliness of surfaces in food processing equipment should be discussed together with hygienic considerations and negative effects due to progressive fouling (reduced heat transfers, increased pressure drop, lower flux through membranes, etc). Cleaning is usually analysed as a heterogeneous chemical reaction involving five major mechanisms: 1. bulk reaction of detergents; 2. transport of detergents into cleaned surfaces; 3. transport to the fouled layers; 4. cleaning reactions, with period of time and liquid energy reserved for physical, chemical, and physiochemical transformation of soil; 5. transport of the reaction products to the interface, and to the bulk solution. The basic inputs to solve the cleaning optimisation procedure are the cleaning kinetics and the amount of liquid energy needed to remove any substance located in a wrong place. This is reported in the literature in relation to design and construction parameters, system, and operational, as well as, specific membrane parameters. In all of them mostly the nature and conditions of surface equipment design are being considered. Moreover, nature and conditions of fouled layer, initial soil amount, water hardness, temperature and concentration of detergent with mechanical action, and the amount of soil contained in the cleaning solution, are also taken into account. Almost all of the above mentioned conditions and parameters of the cleaning system and its technological procedure are strongly related to the amount of liquid energy and parameters of nozzle jet used in this process.

Thus, the purpose of this study was to analyse whether the liquid energy going out from the spray nozzle jet, and the optimisation of its technical parameters, is an adequate description of a cleaning system which should be applied in the Clean In Point (CIP) devices.

2. Liquid jet energy analysis

In most cleaning machines the flow of the cleaning liquid passes through a turbine which is set into rotation. In a very known solution the turbine rotation is through a gearbox transformed into a combined horizontal rotation of the machine body and a vertical rotation of the nozzles. The combined motion of the machine and the nozzles ensures a complete cleaning pattern has been laid for full coverage of the cleaned surface. The number of cycles needed to perform the cleaning process with proper efficiency regarding liquid energy conditions depends on the type of soil age and substances, distance and cleaning procedure, agent, and technical parameters of the equipment used. The speed of the turbine rotation depends on the flow rate through the machine, and on the type of substances, i.e., easy to remove or more heavy soil age (highly viscous, with strong adhesive forces, sticky one, etc.). There is much more important information that has to be understood before cleaning system is designed. The cleaning can be achieved quickly, efficiently and cheaply, or slowly, ineffectively and expensively. The most efficient cleaning process is such which brings the system into satisfactory conditions (Packman 1995) within minimum time, using minimum volume of the cleaning fluid, and with minimal role of manpower.

The assumptions for the liquid jet energy analysis are as follows:

- a liquid going out from jet is examined as a uniform stream (no fine solid particles), entering through the inlet valve (no hydraulic shocks);
- variables characterising the cleaning system and its conditions represent the mean values only;
- a soiled surface is flat and is located perpendicularly to the liquid stream;
- a nozzle jet angle seen as a liquid stream dissipation is constant;
- nozzle jet pressure losses are very small;
- the influence of the nozzle rotation on the liquid parameters is negligible.

On the way from the nozzle mouth to the collision place considered to be the cleaned surface, the amount of liquid jet energy is decreasing. The reason for this is the liquid dissipation energy being observed at the distance from the jet outlet to the surface where some types of substances should be removed. This process has been presented schematically together with some of the jet nozzle technical parameters in Figure 1.

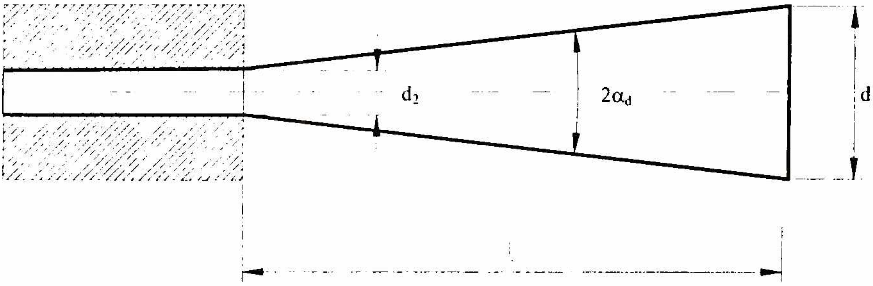

Figure 1. Geometrical data for liquid jet energy analysis

The changes in the amount of liquid jet energy can be described by:

$$E_l = k\,E_2, \tag{1}$$

where E_l [W], and E_2 [W] are liquid jet energies at the cleaned surface and in the nozzle mouth, respectively. The coefficient of energy losses, k, depends on geometric and other constructional parameters of the spray nozzle. Besides, it depends also on the liquid jet distance, l [m], between the nozzle mouth and the cleaned surface. Its total value is the product of three coefficients:

$$k = \alpha\,\gamma\,\mu. \tag{2}$$

The coefficient of the flow intensity, μ, depends on the shape of a hole, the jet–length to diameter ratio, chemical and physical properties of liquid, as well as on the flow conditions like: pressure in the jet nozzle mouth and counter pressure on the liquid's way. Its value can be calculated from:

$$\mu = \varepsilon\beta = (S_{min}/S_2)\,(u_2/u_t), \tag{3}$$

where S_{min} and S_2 [m^2] are the minimal and the exit cross–sections of the liquid jet in the nozzle mouth, respectively, u_2 and u_t [m/s] are real and theoretical liquid jet velocities. The values of μ for various nozzle types have been presented in Table 1. Dependencies of the μ, β and ε coefficients on the Reynolds number for a circular nozzle without sharp edges are presented in Figure 2. For turbulent flow the value of m is constant, and equal to 0.6.

***Table 1.** Coefficient μ values for different nozzle shape [5]*

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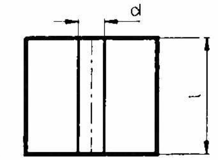
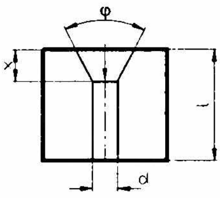
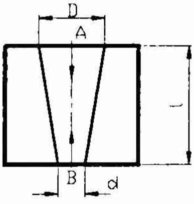
<tr><td rowspan="3">
l=5d</td><td>l/d</td><td>0.5 – 1</td><td>2 - 5</td><td>5*</td></tr>
<tr><td>m</td><td>0.6-0.65</td><td>0.75-0.85</td><td>0.62</td></tr>
<tr><td colspan="4">*for Δp > 3 bar</td></tr>
<tr><td rowspan="3">
l=5d, φ=11°</td><td>x [mm]</td><td>0.5</td><td colspan="2">1 – 2</td></tr>
<tr><td>m</td><td>0.67-0.69</td><td colspan="2">0.9</td></tr>
<tr><td colspan="4">for Δp > 3 bar</td></tr>
<tr><td rowspan="3">
l=5d, D=2d</td><td>direction</td><td>A</td><td colspan="2">B</td></tr>
<tr><td>m</td><td>0.93-0.96</td><td colspan="2">0.62</td></tr>
<tr><td colspan="4">for Δp > 3 bar</td></tr>
</table>

The liquid jet dissipation coefficient, α, describes the influence on the liquid jet angle α_d, and its changes in the liquid cross–section on the way from the nozzle mouth to the cleaned surface α is given by:

$$\alpha = S_2/S_1 = d_2^{\,2}/d_2^{\,2} = d_2^{\,2}/[d_2 + 2l\,\mathrm{tg}(2\alpha_d/2)]^2, \tag{4}$$

where S_1 [m2] is the cross–section of the liquid jet at the cleaned surface, d_1, d_2 [m] are adequate diameters of the cross–sections S_1, S_2, respectively. The values of

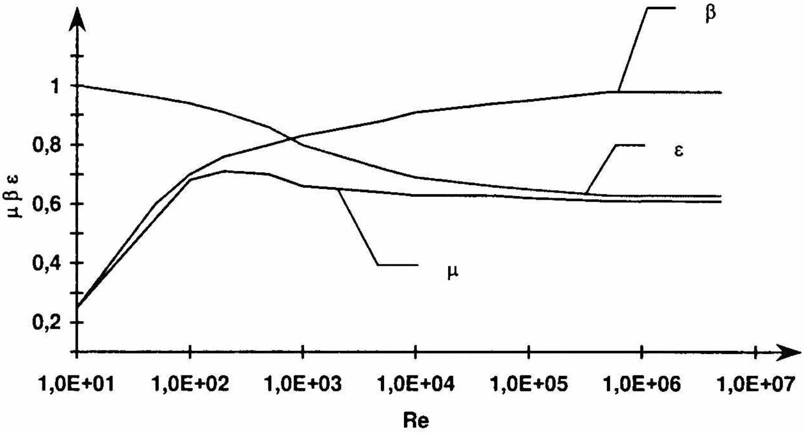


Figure 2. *Coefficients μ, β, ε vs. Re number*

α for different dissipation angles and nozzle diameters calculatated from (4) are presented in Figure 3. It can be observed that when the diameter d_2 and the angle $2\alpha_d$ decrease, the values of α increase.

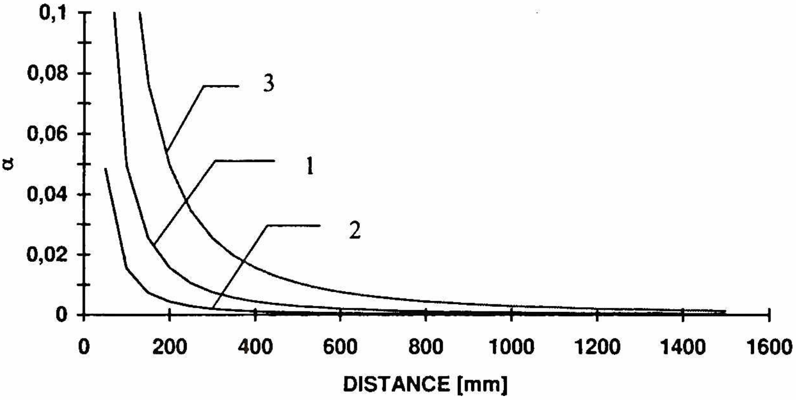


Figure 3. *Coefficient α vs. distance from a nozzle mouth to cleaned surface; 1 $2\alpha_d = 5^0$, $d_2 = 5$ mm; 2 $2\alpha_d = 10^0$, $d_2 = 5$ mm; 3 $2\alpha_d = 5^0$, $d_2 = 10$ mm*

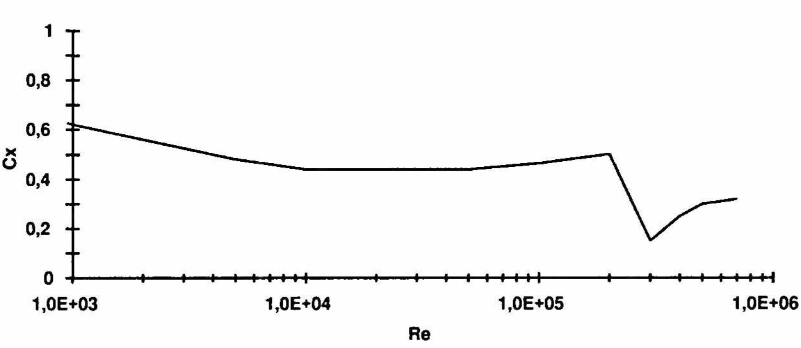


Figure 4. *Coefficient c_x vs. Re number [5]*

The liquid stream dissipation angle $2\alpha_d$ depends on seven variables:

$$2\alpha_d = f(\rho_l, \rho_a, \eta_l, \sigma, u_2, d_2, t), \tag{5}$$

where ρ_l, ρ_a [kg/m^3] are liquid and air densities, respectively, η_l [kg/m/s] is the dynamic liquid viscosity, σ [N/m^2] is the surface tension, t [s] is the cleaning time of a unit surface. Using dimensionless variables the following formula for liquid dissipation angle can be obtained:

$$\mathrm{tg}\, \alpha_d = C\, We^a\, Lp^b\, M^c\, E^d. \tag{6}$$

Here a, b, c, d are the exponents, C is a geometry–dependent coefficient, We is the Weber number, Lp is the Laplace number, and M is the density ratio ρ_a/ρ_l.

The criterion of liquid injection instability, E, is usually taken into account at the initial parts of the liquid stream. The length of this stream fragment, l_b, can be calculated using the following equations: $l_b = 8.85d\, We^{0.25}\, Lp^{0.4}\, M^{0.6}$ (for high counter pressure value), and $l_b = 49.9d\, We^{0.25}\, Lp^{0.4}\, M^{0.24}$ (for low counter pressure value) [5]. The exponents in (6) are given in [5,6], and so the dissipation angle in the essential part of the stream length is given by

$$\mathrm{tg}\, \alpha_d = C\, We^{0.32}\, Lp^{0.07}\, M^{0.5}. \tag{7}$$

In the case of high counter pressure one can assume $We = (140 \div 725) \cdot 10^3$, $Lp = 300 \div 1350$, $M = (0.95 \div 2.8) \cdot 10^{-2}$. For low counter pressure: $M = (0.14 \div 0.95) \cdot 10^{-2}$, and

$$\mathrm{tg}\, \alpha_d = C\, We^{0.32}\, Lp^{0.07}\, M^{0.26}. \tag{8}$$

The values of coefficient C for various nozzles shapes, for both high and low counter pressures, are given in Table 2.

Changes of liquid jet energy related to the air resistance on the way from the nozzle mouth to the cleaned place are described by the drag coefficient γ. Its value can be calculated as:

$$\gamma = e_2/e_1 = 1 - D_e/e_1 = 1 - [(0.5c_x\, \rho_a\, u_2^2)/D_p] = 1 - \rho_a/\rho_l, \tag{9}$$

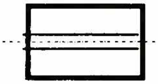
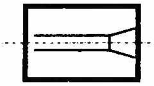
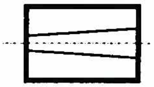
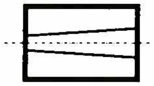
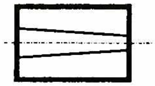
where e_2, e_1 [W/m^2] is the unit liquid jet energy at the cleaned surface, and in the nozzle mouth, respectively, and c_x is the air drag coefficient. Figure 4 shows how the c_x coefficient depends on the Reynolds number. For turbulent flow ($Re > 8000$) the value of c_x is constant, and equals to 0.44.

In view of the above discussion the energy loss coefficient k can be expressed as:

$$k = [\varepsilon\beta d_2^2(1 - c_x M)] \,/\, [d_2 + 2l\, \mathrm{tg}(2\alpha_d/2)]^2. \tag{10}$$

The values of k obtained from (10) are presented in Figure 5. As it is seen, k is strongly related to the distance between the nozzle mouth and the cleaned place. The curves in Figure 5 can be approximated by exponentially decaying function. The remaining parameters have minor influence on k. Thus, the most significant part of the liquid spray jet energy for any useful purpose can be calculated from the k–value only.

Table 2. *Coefficient C values for different nozzle shape [5]; the meaning of symbols as in Table 1.*

Shape of nozzle	High conterpressure	Low conterpressure
 l=2d	0.0089	0.0028
 l=2.5d, $\varphi=11^\circ$	0.0089	0.0028
 l=5d, D=3d	0.005	0.00198
 l=10d, D=3d	0.00831	0.00261
 l=5d, D=2d	0.00513	0.00158

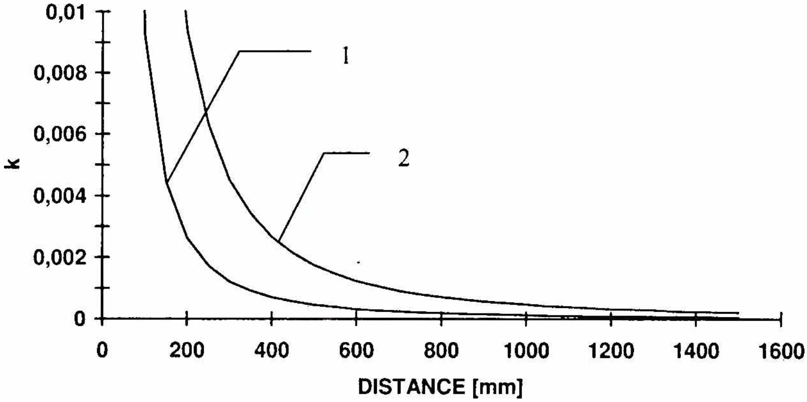


Figure 5. *Coefficient k vs. distance from a nozzle mouth to cleaned surface; 1–* $2\alpha_d = 50$, $d_2 = 5$ *mm,* $u_2 = 10$ *m/s,* $\Delta p = 2\cdot105Pa$*; 2–* $2\alpha_d = 50$, $d_2 = 10$ *mm,* $u_2 = 15$ *m/s,* $\Delta p = 2\cdot105Pa$

3. Optimisation of jet parameters

The basic criteria for optimisation of the spray nozzle jet parameters usually being considered in such cases, are the amounts of energy and water consumption. The minimisation of these two values is the main task in design of many industrial cleaning–systems. This is also a ways for looking for more rational and economical cleaning processes together with the highest possible efficiency of removing of any kind of soil. Basically, the cleaning process consists of, and can be divided into three phases: a fouling soaking, a fouling rinsing, and a fouling separating. From this point of view, it is necessary to stress that the second phase has a decisive meaning for the efficiency of the cleaning process. That efficiency depends also on the type of fouling at the cleaned surface; its adhesives forces, and the type of the cleaning medium. On the other hand, it is important which components are included, i.e., alkaline, acid, as well as detergents, anticorrosive and water softening additives, etc. The basic jet parameter is the pressure in the spray nozzle jet mouth. The value of this pressure will determine all other important parameters: flow volume, liquid jet velocity, and liquid jet energy going out from the nozzle mouth. The next important factor for process optimisation of spray nozzle jet parameters is the energy loss coefficient, because of its significant influence on the minimum energy needed to remove certain type of fouling. The minimum energy, which is necessary to remove the fouling from the cleaned surface, can be described by the following equation:

$$E_1 = eS_1 = 0.25e\pi\,[d_2 + 2l\,\mathrm{tg}(2\alpha_d/2)]^2, \tag{11}$$

where $e = fl\,\pi/t$ [W/m^2] is the unit cleaning energy, and f [N/m^2] is the unit cleaning force.

Adequate evaluation of the unit cleaning force needed for each type of fouling should be determined by laboratory experiment. It is common knowledge that each fouling process is a resultant consequence of an adhesive force appearing between type of soil and surface in contact. A lot of influences are being observed in the theory used for explanation of the fouling process. It is obvious that chemical composition of fouling, thickness of fouling layer, and quantity of micro–organisms play main role in creating difficulties for cleaning process and in amount of energy requested for proper sanitation standard. The liquid nozzle energy can be described by:

$$E_2 = \Delta\mathrm{p} = S_2u_2\Delta\mathrm{p} = 0.25\pi d_2^{\,2}\Delta\mathrm{p}(2\Delta\mathrm{p}/\rho_1)]^{1/2}, \tag{12}$$

where Q [m^3/s] is the flow volume. After calculations the formula for the pressure in the spray nozzle jet mouth is:

$$\Delta\mathrm{p} = [e_2\rho_1/(2k^2\alpha^2]^{1/3}. \tag{13}$$

Using

$$B = [\rho_1/(2k^2\alpha^2]^{1/3}, \tag{14}$$

the pressure in nozzle jet mouth can be written as:

$$\Delta\mathrm{p} = B_2 \times e_2^{\,2/3}. \tag{15}$$

The value of B is independent of the cleaning liquid and of the spray nozzle jet parameters. In Figure 6 the pressure changes in the spray nozzle for various unit cleaning energies and values of B are presented.

After calculation of the pressure in the spray nozzle mouth, it is necessary to recalculate the value of k, the volume flow, and the liquid dissipation angle. For the volume flow the following formula can be used:

$$Q = [\mu S_2(2\Delta p \times \rho_1). \tag{16}$$

For exemplary calculations let us take into account the following data: $We = 704000$, $Lp = 44000$, $M = 0.0014$, $C = 0.0028$, $c_x = 0.44$, $l = 1$ m, $d_1 = 2$ m, $d_2 = 4$ mm, $\rho_l = 1100$ kg/m^3, $\rho_a = 1.29$ kg/m^3, $\mu = 0.6$, tg $\alpha_d = C\ We^{0.32}\ Lp^{0.07}\ M^{0.26}$. The pressure in the nozzle mouth versus time is presented in Figure 7, whereas the remaining results are shown in Figures 8–12. The calculations were performed using the Matlab programme.

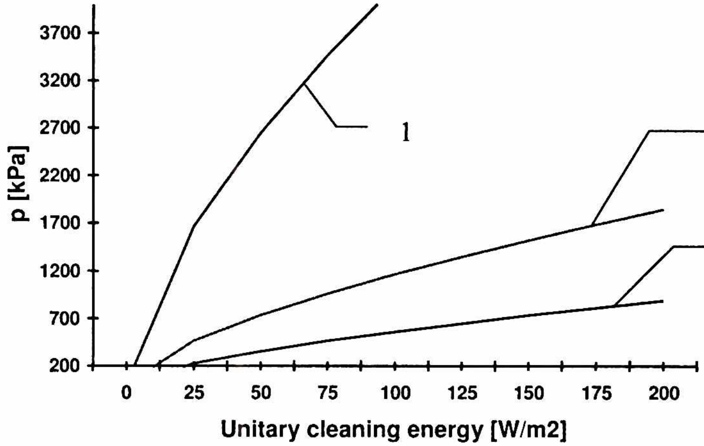


Figure 6. *Pressure in the nozzle mouth vs. the unitary cleaning energy; 1– B = 195 000, 2– B = 54 000, 3 – B = 26 000*

4. Concluding remarks

In the light of the considered relationship between the amount of energy in the nozzle mouth and the one needed to remove fouling, it is clear that the main factor explaining these changes is strongly dependent on the distance.

Our numerical analysis indicates, that the energy required by the cleaning system can be calculated basing on the energy loss coefficient only, which provides an adequate description of the cleaning process.

Coefficient k within each cleaning system depends on the geometry of the spray nozzle jet, as well as on the liquid parameters. Our k–coefficient–method seems to be the best approximation of the behaviour of both spray nozzle jet and liquid energy together with their efficiency at the cleaned surface.

Basing on the results on the liquid spray nozzle energy and its parameters, it can be stated that our concept is very useful for adequate description and optimisation of each part of the cleaning system.

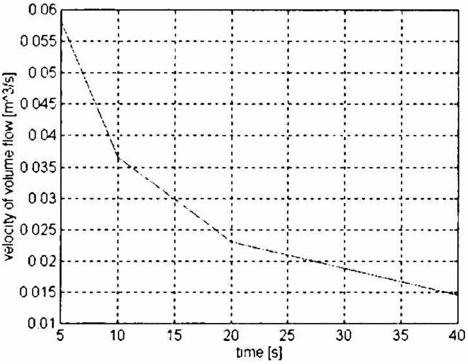


Figure 7. Pressure in the nozzle mouth vs. time

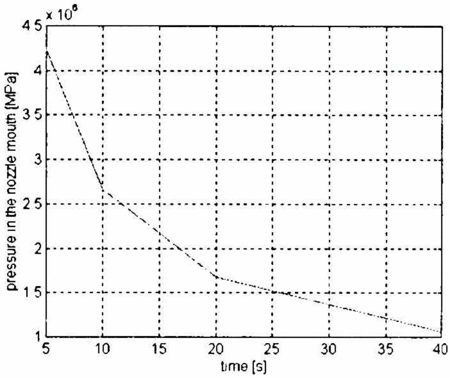


Figure 8. Velocity of volume flow vs. time

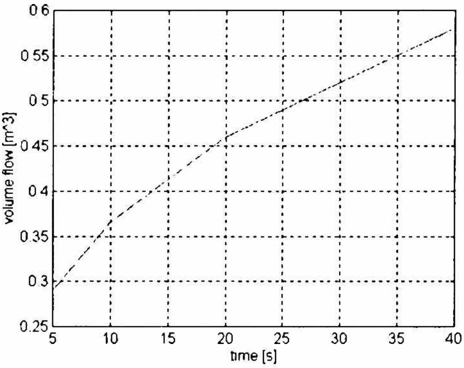


Figure 9. Volume flow vs. time

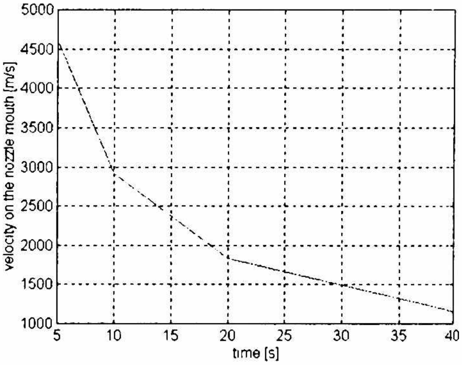


Figure 10. Velocity of liquid in the nozzle mouth vs. time

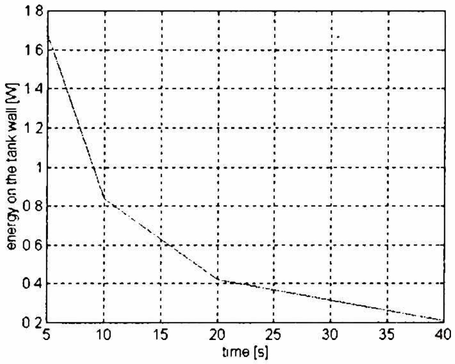


Figure 11. Liquid energy in the nozzle mouth vs. time

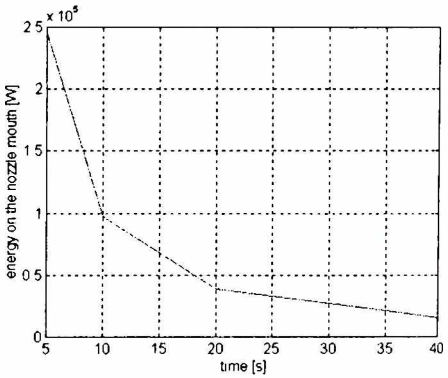


Figure 12. Liquid energy at the cleaned surface vs. time

However, it is understandable that in order to describe various aspects of real cleaning systems, reliable data on the unit energies, taken from precise laboratory measurements, should be taken into account.

Acknowledgement:

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