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MILLING OF MATERIALS BY WATER JETS – ACTING OF LIQUID JET IN THE CUTTING HEAD

MLETÍ MATERIÁLŮ VODNÍMI PAPRSKY - PŮSOBENÍ KAPALINOVÉHO PAPRSKU V ŘEZNÉ HLAVICI

Abstract

Procedures leading to the utilisation of a liquid jet as a tool suitable for material milling are usually based on the suction of material particles of a suitable medium size into the mixing chamber and the focusing tube. In this system, called a cutting head, physical processes take place, which cause, or may cause, damage to the particles of material. The determination of an extent of changes in the size of particles induced in the cutting head, both theoretical and experimental, is the main objective of this article, because the knowledge of size of particles at the exit from the cutting head is necessary for studying subsequent processes which are to support the milling effect of liquid jet: the impingement of a jet containing material particles on a target of very resistant material or the collision of two such jets moving in the opposite directions.

Abstrakt

Základem postupů směřujících k využití kapalinového paprsku jako nástroje vhodného pro mletí materiálů je zpravidla nasávání částic materiálu vhodné střední velikosti do směšovací komory a usměrňovací trubice. V této soustavě, nazývané řezná hlavice, nastávají fyzikální procesy, které způsobují, nebo mohou způsobit, porušování částic materiálu. Stanovení míry změn ve velikostech částic způsobených v řezné hlavici, a to teoreticky i experimentálně, je hlavním cílem tohoto článku. Znalost velikosti částic na výstupu z řezné hlavice je totiž nutná při studiu návazných procesů, které mají podpořit mlecí efekt kapalinového paprsku: dopad paprsku obsahujícího materiálové částice na terč z velmi odolného materiálu nebo střet dvou takovýchto paprsků při protiběžném pohybu.

1 INTRODUCTION

In the year 2005 the project dealing with the milling of particles of brittle materials with liquid jets was launched at the Section of Liquid Jet at the Institute of Physics of VŠB-Technical University of Ostrava, which research into the process of parting (cutting) and machining materials preceded. In the framework of research focused on material cutting, cutting heads (usually supplied commercially) were used, in which a liquid jet of high velocity (500 to 1000 $m.s^{-1}$) makes it possible to suck in, accelerate and direct the abrasive particles/air mixture [1, 2]. The resultant mixture of liquid, abrasive particles and air increases the efficiency of material cutting process. The abrasive water (liquid) jet generated by this technique is usually called injection jet.

Research works have also revealed [3 to 11] that in this system, not only acceleration or focussing of abrasive particles takes place but also partial destructing these particles occurs – grinding, splitting, internal disturbing. These processes lead to a reduction in the weight of particles to the detriment of cutting process.

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The grinding of materials in the course of mixing process, which is a negative phenomenon of the process of generation of injection abrasive water jet intended for cutting, is used to the advantage of milling process. The cutting head was utilised for the development of new liquid mills. The goal of next research efforts was thus theoretical-experimental research into the behaviour of liquid jet in processes leading to the disintegration of input particles of medium size of 0.2 - 0.3 mm (approximately 80 mesh) to micron particles and submicron particles.

This article, introducing into the problem of particle disintegration by liquid jets, deals with the interaction between the water jet and input particles in the mixing chamber and the focusing tube. It is aimed namely at the process of particle destruction in this system (i.e. in the cutting head).

2 THEORETICAL BACKGROUND OF MATERIAL MILLING IN THE COURSE OF ITS SUCTION INTO THE LIQUID JET

A diagrammatical section through the cutting head of basic design is shown in Fig. 1. From the theoretical model of collision between the liquid jet and particles of material [5] it follows that a certain degree of wear of these particles (grains) occurs already after their entry into the mixing chamber. At least four processes that can cause damage of particles inside mixing chamber can be expected there.

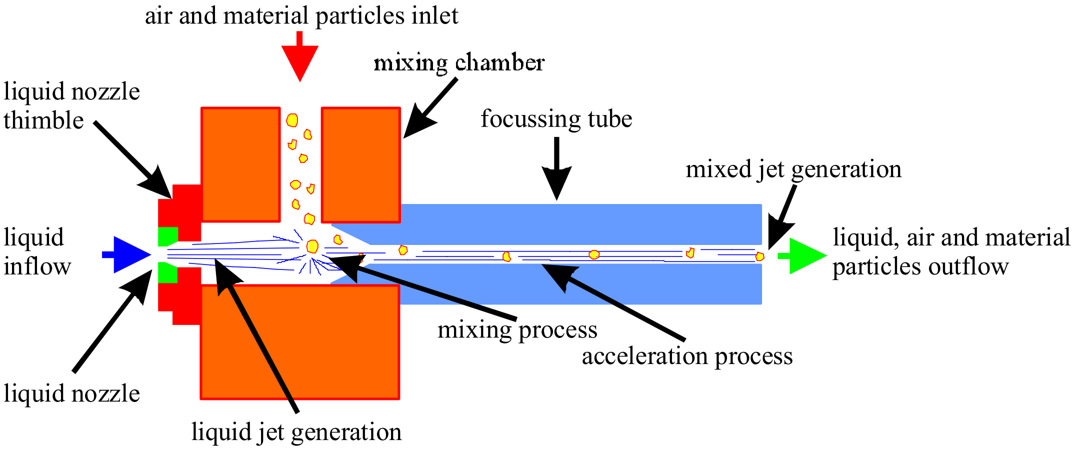

Fig. 1. A diagrammatical section through the cutting head of abrasive water jet with the representation of processes leading to the generation of abrasive liquid jet at its exit.

The first process of disintegration (crushing) takes place at the collision of grains with the water jet of high velocity. The water jet is generated inside a liquid nozzle and its velocity depends on the pressure of water ahead of it (ideal velocity is up to 910 $m.s^{-1}$ at the pressure of 415 MPa). The higher is the velocity of liquid jet, the higher is its energy and the more favourable are conditions for acceleration of particles in the system. Particles which get into a contact with the liquid jet are, however, almost stationary in the direction of liquid jet flow. The impact of liquid jet causes in them a rapid growth in mechanical stresses, which lead even to the production of internal failures or the disintegration of original particles to lesser ones. Particles are not only accelerated in the direction of liquid jet flow, but some of them are shot to the walls of mixing chamber and entrained in a chaotic way into the focusing tube. The second process of disintegration of particles occurs when the particles strike the walls of the mixing chamber and the focusing tube. The third process of disintegration, during which particles are further ground and damaged, is represented by collisions of particles between each other. The fourth process which may damage the particles in the mixing process covers cavitation phenomena, because the jet is aerated, which supports the cavitation processes. The basic model for the prediction of sizes of particles and their distribution functions was published in the years 1995 and 1996 [4, 5].

For the reason of determination of velocity of the mixture of abrasive particles and liquid at the exit from the focusing tube, a theory was worked out which made it possible to determine the loss coefficient of momentum at accelerating particles in the mixing system. The velocity of particles accelerated by the liquid jet at the exit from the focusing tube can also be calculated by the iteration method based on the description of force acting at the collision of liquid jet, material particles and tube walls [2]. The liquid jet is to be represented by suitable approximative spatial elements (spheres, cylinders). The method of calculation is time-consuming and its accuracy is significantly influenced by the justification of physical approximations [2, 4, 5, 6]. That is why for the calculation of liquid jet velocity with the sucked material, a common equation (1) is used, which follows from the law of momentum conservation in the system of liquid and material particles at the derivation of physical description of generation of the abrasive water jet, see e.g. [12]. The resultant velocity is determined from the flow rates of liquid and particulate material mixing with water. Sucked air is, owing to its negligible weight with regard to the other components, neglected:

$$v_a = \delta \, v_o \, \frac{m_w}{m_w + m_a} \tag{1}$$

To make the calculation more accurate, the coefficient δ characterising the transfer of momentum, is expressed by the product of several coefficients [13]. Those make it possible to determine better the influences of processes taking place in the mixing chamber and the focusing tube ($\delta = C_1 C_2 C_3 C_4$). The importance of coefficients is together with relationships for the determination of them given in the following paragraphs.

Coefficient C_1 decreases the velocity of resultant liquid jet with the particulate material of solid phase in case that the number of particles of original size entering into the interaction space exceeds a possibility of breaking and accelerating them by the liquid jet.

$$C_1 = \frac{\pi \, \rho_a \, v_o \, a_o^3}{3 \, d_o \, m_a} \quad \text{and for} \quad \frac{3 \, m_a}{\pi \, \rho_a \, a_o^3} \le \frac{v_o}{d_o} \quad \text{it is true that} \quad C_1 = 1 \tag{2}$$

Coefficient C_2 decreases the velocity of liquid jet with the particulate material of solid phase in case that the number of particles of newly formed size exceeds possibilities of developed flow in the focusing tube; i.e. the particles obstruct each other's motion.

$$C_2 = \frac{d_a}{\sqrt{6} \, a_n} \quad \text{and for} \quad d_a > \sqrt{6} \, a_n \quad \text{it is true that} \quad C_2 = 1 \tag{3}$$

Coefficient C_3 determines a decrease in the velocity of liquid jet with the particulate material of solid phase due to the friction of particles against the walls of the focusing tube and it is related to a certain material, the material of focusing tube and the length of this tube.

$$C_3 = \left(1 - f \, \frac{l_a}{l_{ao}} \right) \tag{4}$$

Coefficient C_4 makes it possible to calculate a decrease in the velocity of liquid jet with particulate material of solid phase due to the ratio between the diameter of the liquid nozzle and the diameter of focusing tube.

$$C_4 = 1 - \frac{(2 \, a_n + d_o)}{2 \, d_a} \quad \text{for} \quad d_a > 0 \tag{5}$$

Relevant theoretical prediction distribution functions for original and milled abrasive 80 mesh particles of one kind without internal failures are represented by curves in a graph in Fig. 2. For calculations, the mean values determined for an Australian garnet were used as material parameters. The reason is that the Australian garnet is a material, which is the most easily available for our experiments at present. What a disadvantage of it is the fact that it is neither of only one kind nor composed merely of undisturbed grains, and thus a comparison of experimental results with this ideal theoretical approximation shows certain deviations. Nevertheless, general rules can be observed even on the simplified model. They are in accordance with the results of experiments, although they were obtained on a far more complicated system of particles than in this mentioned model case.

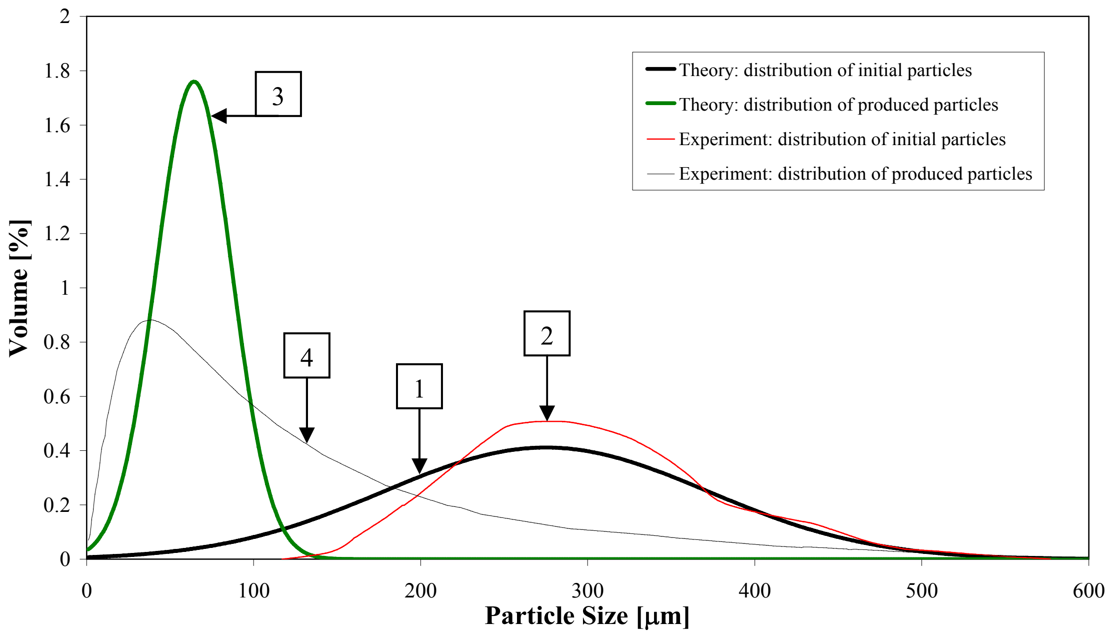

Fig. 2. A graphic comparison of the distribution of particles determined by calculation from the theoretical model by Hlaváč with the distribution determined experimentally: 1 – curve calculated from Hlaváč's model for input spherical homogenous abrasive 80 mesh particles of Australian garnet, 2 – curve determined for input particles from experimentally determined values, 3 – curve calculated from Hlaváč's model for spherical homogenous abrasive particles of Australian garnet produced from input 80 mesh particles in the course of passing through the cutting head under pressure of 400 MPa, 4 – curve determined for generated particles by experimental research.

3 PERFORMED EXPERIMENTS WITH MIXING CHAMBERS AND THEIR RESULTS

The goal of input experiments was to obtain data on the influence of mixing chamber of several different designs and a ratio between the diameter of focusing tube and the diameter of water nozzle. Various configurations (marked A, B, C) of mixing chambers were tested (see Fig. 3). These experiments were to clarify whether or not additional processes, included after this necessary input system (e.g. interaction with the fixed target or collision between jets moving in the opposite directions), caused a substantial increase in the amount and a decrease in the size of disintegrated particles.

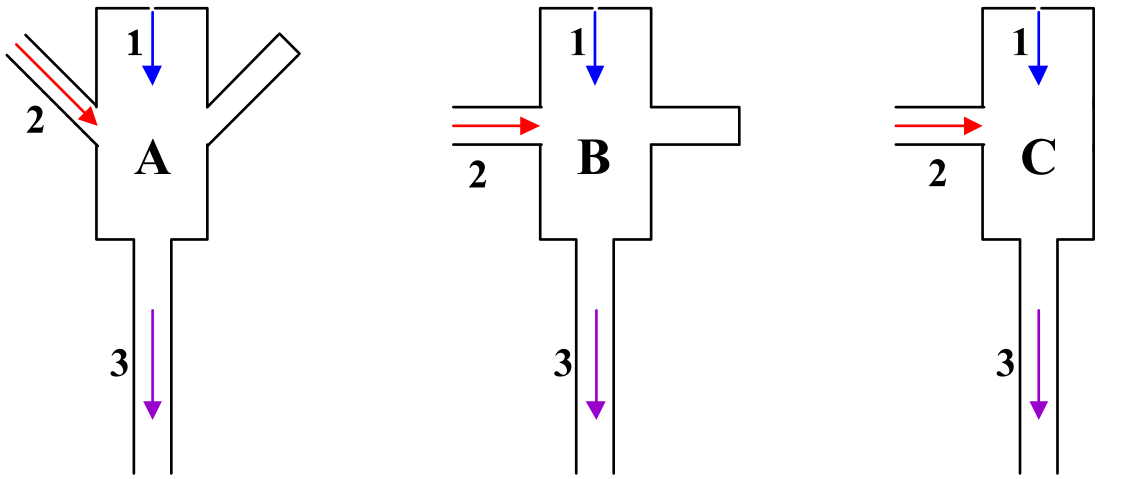

Fig. 3. Diagrammatical sections through various configurations of mixing chambers used for the generation of abrasive water jet: 1 – water jet; 2 – mix of sucked air and material particles; 3 – outflow of the mixed jet; A, B, C – mixing chamber configurations.

After passing through the mixing chamber and the focusing tube (after the suction of material particles), the water jet was directed to the axis of tube of diameter of 0.15 m and length of 2 m (Fig. 4), where it was damped by interaction with the air naturally to such an extent that in the bent part, which directed the stream into the catch tank, any substantial destruction of particles took place no more. The axis of jet and the axis of focusing tube delimiting space for the jet flow lay in the plane horizontal towards the earth surface. In this way it was possible to get, after the analysis of entrapped product, a picture of whether or not the particles were substantially comminuted by the mere mixing process.

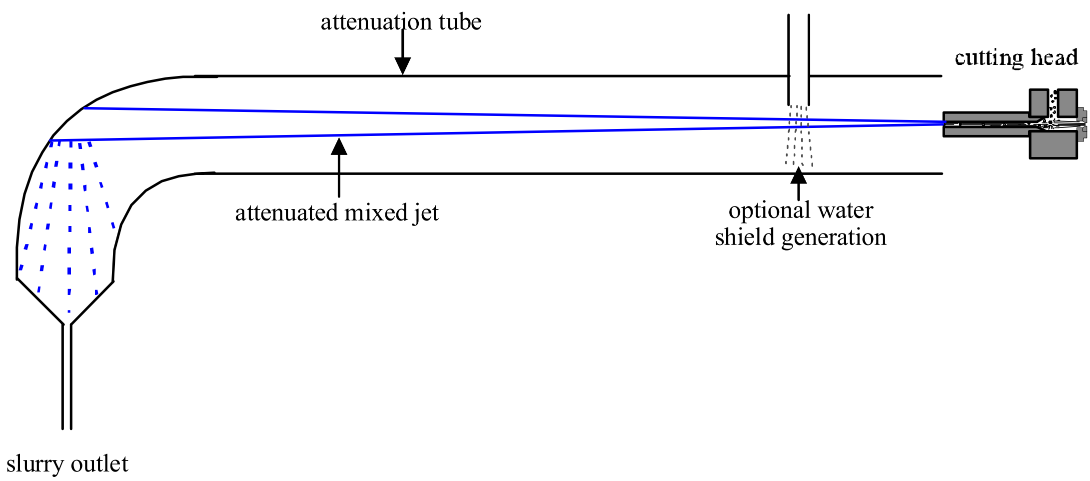

Fig. 4. A diagram of experimental set-up at the interception of (abrasive) mixed liquid jet.

For our initial tests the following parameters were selected as variables: the type of mixing chamber, the kind of focusing tube and a ratio between the diameter of focusing tube and the diameter of water nozzle. The experimental verification of acting of other parameters, the influence of which on the process of destruction of particles in the mixing system is described theoretically (liquid pressure, amount of sucked material, size of input particles), will be the subject of following research activities.

Three types (or designs) of mixing chambers (Fig. 3) and two kinds of focusing tubes (Fig. 5) were available. The focusing tubes designated 1 could be used merely in combination with the A type of chamber; however, they were available in four inner diameters and three lengths (Tab. 1). The focusing tubes 2 could be used with chambers of B and C types, but they were available only with one inner diameter and one length. In the course of experiments with the chamber of A type fitted with a 0.25 mm diameter of the water nozzle and the focusing tubes designated 1, it was found that with the increasing diameter of focusing tube, the effectiveness of milling decreased (a higher share of coarser resultant fraction was found). This expected physical trend is clear from the experimental results – the analysis of sizes of particles of obtained products, which are presented in a form of graphs in Fig. 6.

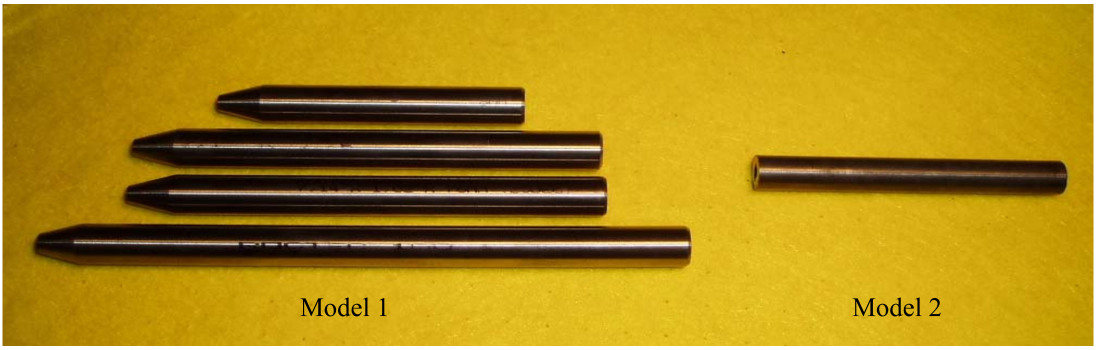

Fig. 5. Kinds of focusing tubes used in experiments.

Tab. 1. Combinations of mixing chambers and focusing tubes.

Focusing Tube	Mixing Chamber type A	Mixing Chamber type B	Mixing Chamber type C
Model 1, diameter 0.51 mm, length 51 mm	**X**	-	-
Model 1, diameter 0.76 mm, length 76 mm	**X**	-	-
Model 1, diameter 1.02 mm, length 76 mm	**X**	-	-
Model 1, diameter 1.52 mm, length 138 mm	**X**	-	-
Model 2 (samples a, b), diameter 0.51 mm, length 51 mm	-	**X**	**X**

From the comparison of distribution curves determined for the products obtained from various configurations of chambers, nozzles and focusing tubes, some rules of importance to the next work in the area of water jet comminution of materials follow. Above all it can be stated that at the fixed diameter of water nozzle, the proportion of finer fraction increases if we decrease the diameter of focusing tube (Fig. 6). The proportion of finer fraction, however, drops when shortening the length of this tube. Both the presented conclusions are in accordance with the logic of processes taking place in the course of mixing in the head and the focusing tube. Another logical assumption, the experimental confirmation of which is very important, is that the mixing chamber of type A with an oblique inlet for abrasive particles (PaserIII®) causes a markedly lower destruction of sucked material than mixing chambers with a perpendicular inlet for particles (types B and C) at comparable setting the other parameters: the pressure of liquid, the diameter of water nozzle, the diameter and the length of focusing tube, the amount of sucked material (Fig. 7). As can be seen in Fig. 8, the head JetEdge (type C) together with a small diameter of water nozzles forms not only a very low proportion of fine fraction of about 1μm, but, in contrast to other tested configurations, also a low volume proportion even of particles of size of about 10μm. From the point of view of milling effects, it is possible to also mention the fact that the application of spraying water through which the jet passed with entrained particles in one of tested cases, has probably positive, although not resounding influence on reduction in particle size (Fig. 9).

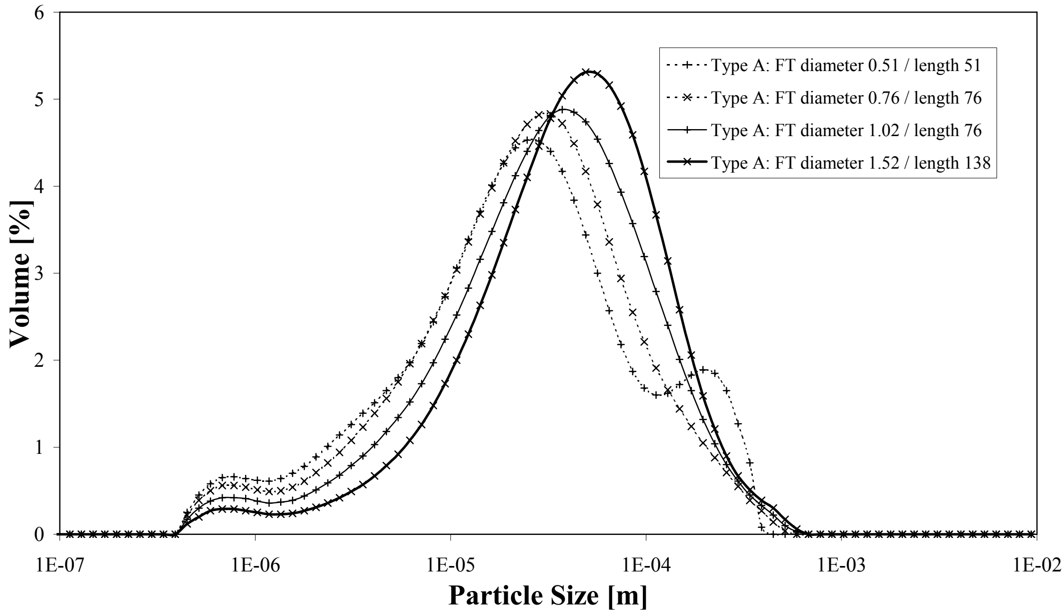

Fig. 6. Experimental results of determination of the volume percentage of particle size for the mixing head of type A and the focusing tubes (FT) of various diameters and lengths at the constant diameter of the water nozzle of 0.25 mm and the pressure of water ahead of the water nozzle of 400 MPa.

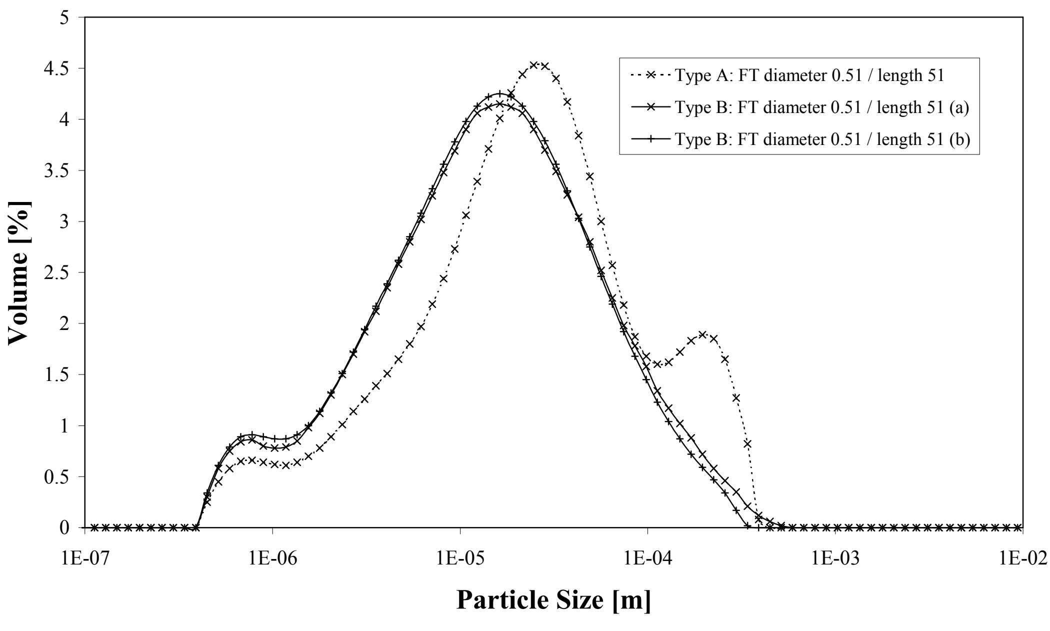

Fig. 7. Experimental results of determination of the volume percentage of particle size for various mixing heads (A, B) at the diameter of water nozzle of 0.25 mm, pressure of 400 MPa and the focusing tube (FT) with the same inner diameter and length.

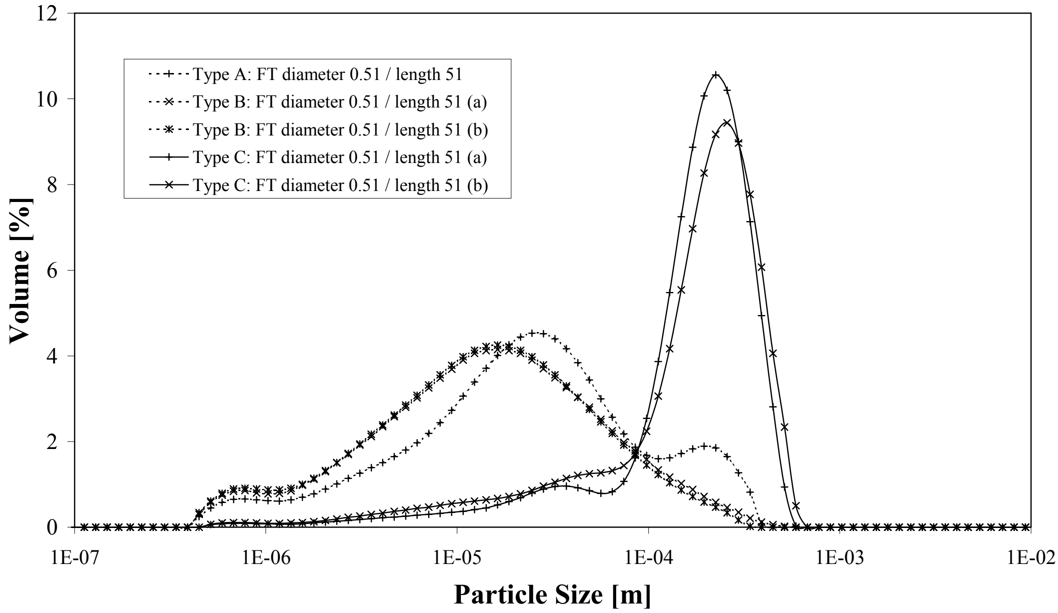

Fig. 8. Experimental results of determination of the volume percentage of particle size for heads A, B (diameter of water nozzle of 0.25 mm, pressure of 400 MPa) and C (diameter of water nozzle of 0.15 mm, pressure of 400 MPa) with the focusing tubes (FT) with the same diameter and the length.

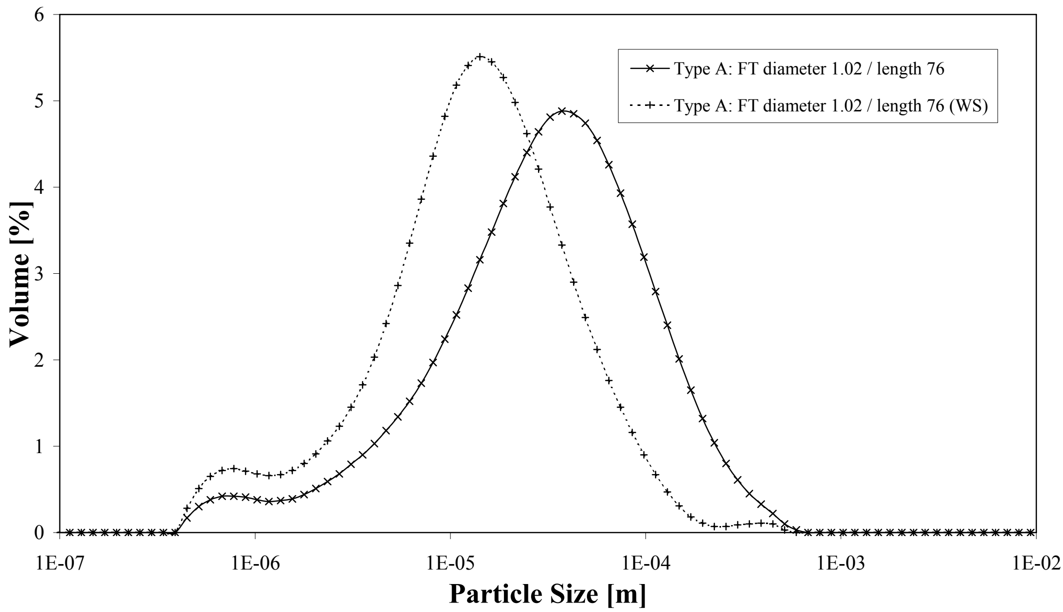

Fig. 9. Experimental results of determination of the volume percentage of size of particles got with or without water spraying (WS) under otherwise equal conditions.

4 COMPARISON OF EXPERIMENTAL RESULTS AND THE ONES CALCULATED FROM THE THEORETICAL MODEL

The model of interaction between the liquid jet and material particles in the mixing chamber and the focusing tube, published in the years 1995 to 1998 [4 to 8], forms the basis of comparison. Interaction can be examined on the basis of several physical approaches. Attention is focused on a proper collision between the jet and the element of material, because physical derivations indicate that at this collision, a sharp increase in the stress in material particle takes place and thus the particle may be damaged or broken. At experiments aimed at research into abrasive liquid jets it has really been found that the original grain size of abrasive material changes already in the mixing chamber and the focusing tube. In the subsequent theoretical and experimental analysis it has been found that by modelling the behaviour of some materials in the course of suction into the liquid jet, tasks of interaction between the liquid stream and elements of material may be solved as well. Physical relationships describing the origin of new particles due to interaction between the liquid jet and particles of material in the course of ejector-based suction are presented as (6) to (8) [5]. The surface, which will be formed by transforming interaction energy to material damage, can be described by the following equation

$$P_N = \frac{C_D \pi a_o d_o^2 \mu^2 p_o^2 \gamma_R^2}{16 \rho_o E_P c_o^2} \tag{6}$$

The mean size of newly formed particles (on physical simplification that both original and newly formed particles are of cubical shape) can be then calculated from the equation given below

$$a_n = \frac{24 \rho_o E_P c_o^2 a_o^3}{24 \rho_o E_P c_o^2 a_o^2 + C_D \pi a_o d_o^2 \mu^2 p_o^2 \gamma_R^2} \tag{7}$$

For the purpose of comparing the theory and the experiments, it is suitable to introduce a distribution function, which determines a probability of occurrence of certain size of newly produced particles. The distribution function is defined by a relationship derived from the Gaussian distribution (see particle statistics presented in Fig. 2)

$$P_D = \frac{100}{C} e^{-4\frac{(x-a_n)^2}{(a_o-a_n)^2}} \tag{8}$$

Equation (8) makes it possible to determine not only the probability of occurrence of new particles of chosen size, but also the distribution curve. In addition, the theoretical model allows the determination of dependence of size of newly generated particles on the pressure of liquid before the liquid nozzle or on the mean size of input particles, if the parameter is the pressure of liquid before the liquid nozzle.

The comparison between the model and the experiments is possible thanks to the distribution curves plotted in Fig. 2. In calculations, parameters of experimental material – Australian garnet – were used in the presented theoretical model. Experimentally determined curves correspond to the distribution functions for input particles of Australian garnet and for particles produced during the mixing process at the classical configuration of cutting head used for standard cutting.

5 CONCLUSIONS

From the results presented in this article, especially the following conclusions may be drawn:

- in the mixing chambers with an oblique inlet for abrasives, under otherwise comparable experimental conditions, the lower percentage of particles with very small sizes is produced than in the mixing chambers with a perpendicular inlet for abrasives – milling effect is smaller;
- with the growing diameter of focusing tube at the constant diameter of water nozzle and other parameters, the milling effect caused by processes in the mixing chamber and the focusing tube diminishes;

- with the decreasing diameter of water nozzle, the milling effect of processes in the mixing chamber and the focusing tube diminishes;
- theoretical relationships derived by Hlaváč for the calculation of disintegration of particles in collision between the particles and the liquid jet in the mixing chamber and the focusing tube provide results, which are in accordance with the results of experiments.

Acknowledgements
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List of used symbols

a_o the original mean size of material particles ...[m]

a_n the mean size of particles produced in the course of mixing process ...[m] (when used as the limit traverse rate …[m.s^{-1}])

c_o the velocity of sound in liquid ...[m.s^{-1}]

C the standardising constant of a distribution function ...[-]

C_1 the coefficient characterising a decrease in the velocity of an abrasive jet as a result of clogging the liquid jet with abrasive at increasing the abrasive material flow ...[-]

C_2 the coefficient characterising a decrease in the velocity of an abrasive jet at exceeding the limit ratio between the mean size of the newly produced particles of abrasive material and the diameter of the focusing tube ...[-]

C_3 the coefficient modifying the velocity of an abrasive jet as a result of friction of abrasive particles against the walls of the focusing tube according to the length of tube towards the standard ...[-]

C_4 the coefficient modifying the velocity of an abrasive jet according to the value of instantaneous ratio between the diameter of the liquid nozzle, the mean size of the abrasive grain and the diameter of the focusing tube towards the optimum value of this ratio ...[-]

C_D the coefficient of resistance of material particle in the flow of liquid ...[-]

δ the cumulative coefficient of efficiency of transformation of momentum in the mixing process …[-]

d_o the diameter of water nozzle ...[m]

d_a the diameter of focusing tube ...[m]

E_P specific energy needed for the formation of a unit free surface in material (specific surface energy of material) ...[J.m^{-2}]

f the coefficient of friction of abrasive particles against the walls of focusing tube ...[-]

γ the compressibility of liquid at pressure p_o ...[Pa^{-1}]

γ_o the compressibility of liquid at normal pressure ...[Pa^{-1}]

γ_R abbreviated relationship $\left(1-\gamma p_o\right)$ ...[-]

μ the loss coefficient of the nozzle ...[-]

m_a the mass flow rate of abrasive ...[kg.s^{-1}]

m_w the mass flow rate of liquid ...[kg.s^{-1}]

p_o the pressure of liquid before the nozzle (in the pump) ...[Pa]

P_D the probability of generation of particles of a new diameter ...[-]

P_N the newly produced surface ...[m^2]

ρ_a the density of abrasive material (or material for milling) ...[kg.m^{-3}]

v_o the velocity of liquid jet without admixtures at the exit from the nozzle ...[m.s^{-1}]

v_a the velocity of abrasive jet at the exit from the focusing tube ...[m.s^{-1}]

ρ_o the density of liquid under standard conditions ...[kg.m^{-3}]

x the variable distribution function ...[m]

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