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Mathematical model for determining the expenditure of cooling and lubricating fluid reaching directly the grinding zone

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ABSTRACT

Purpose: The purpose of this article is to discuss the method of determining the mathematical model used for calculating the amount of emulsion reaching directly the grinding zone during the hob sharpening process.

Design/methodology/approach: The mathematical model, in the form of a multiple regression function, was determined based on the acceptance and rejection method. The data for the calculations was obtained by conducting numerical simulations of fluid flow in the Ansys CFX software.

Findings: A mathematical model enables calculating the amount of efficient expenditure of emulsion reaching directly the zone of contact between the grinding wheel and workpiece (hob cutter rake face) at various nozzle angle settings and different nominal expenditures of emulsion. The verification of the mathematical relationship confirmed its accuracy.

Research limitations/implications: Further research should focus on the other types of grinding process and other types of cooling and lubricating fluids.

Practical implications: The mathematical model enables a selection and application in the workshop and industrial practice of various variants of emulsion supply during the grinding of hob cutter rake face. Analysis of the multiple regression equation created on the basis of the acceptance and rejection method also allows predicting changes in the analyzed numerical model.

Originality/value: The literature review has shown that no research of this type has been conducted with regard to analyses and optimisation of the grinding process during hob cutter sharpening. The results of this research are a novelty on a worldwide scale.

Keywords: Numerical techniques, Statistic methods, Grinding, Coolant, CFX

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

RESEARCH PAPER

1. Introduction

The cooling and lubricating fluids are commonly applied in various types of the grinding process. This stems directly from the functions they perform, that is, among others [1]:

- cooling the workpiece and grinding wheel active surface through absorption and dissipation of the heat created,
- forming a stable layer of lubricant that reduces friction between the abrasive grit and the workpiece, as well as between the binder and the workpiece,
- moisturising and cleaning the grinding wheel active surface.

In the literature there are no comprehensive studies or elaborations regarding application of cooling and lubrication fluids during sharpening of cutting hobs. The authors of the few pieces of information available usually provide only the recommendation to apply the cooling and lubrication fluid in generous amount [2,3]. The commonly applied method for supplying a generous amount of emulsion to the grinding zone is the flood method [4-7]. In this method, the cooling and lubricating fluid is transported by means of a pump and directed through a nozzle or multiple nozzles with a slot opening into the zone of contact between the grinding wheel and the workpiece. The basic cooling and lubricating fluid applied in the flood method is water oil emulsion formed as a result of diluting the oil concentrate with water, where the oil content in the emulsion is usually between 2% and 5% [6,7].

From the available publications regarding other varieties of the grinding process it is known that one of the significant inconveniences of application of the conventional flood method is the so-called air cushion phenomenon. It is caused by the rotary movement of the grinding wheel and manifests itself in the form of a spinning stream of air surrounding the grinding wheel around its circumference [1,8]. The research described in the paper [4] indicates that deflection and spraying of the emulsion stream takes place already at the peripheral speed of v_s=20 m/s, hindering its contact with the active surface of the grinding wheel and limiting severely the access of emulsion to the grinding zone. Thus, only a small portion of volume of the processing fluid supplied penetrates the zone of contact between the grinding wheel and the workpiece. In view of that, attempts are made to ensure such conditions of processing that enable the largest possible portion of emulsion supplied to the grinding zone to reach directly the zone of contact between active abrasive grit and the workpiece.

The basis for evaluating the efficiency of different conditions of supplying cooling and lubrication fluids to the grinding zone are the experimental studies of condition of material surface after grinding. The review of literature showed that the distance of the emulsion feeding nozzle from the grinding zone and the angular alignment of the nozzle with regard to the active surface of the grinding wheel are the factors having the greatest influence on efficiency of the impact of the cooling and lubricating fluid on the results of processing [9,10]. The disadvantage of these studies is that, it is impossible to establish the amount of emulsion reaching directly the zone of contact between the grinding wheel and the workpiece. Such information can be obtained by conducting numerical tests that simulate the flow of emulsion during grinding. It is possible to create on their basis a mathematical model describing the impact of grinding condition on the amount of expenditure of emulsion reaching directly the grinding zone.

This article discusses the method of determining the mathematical relationship for calculating the amount of emulsion reaching the grinding zone during the hob cutter grinding process. It was assumed the this amount will be described as the $Q_{WET\text{-}OUT}$ efficient expenditure. The data for calculations was obtained by conducting numerical tests. During the numerical tests there was simulated the flow of water oil emulsion which hits the active surface of the grinding wheel after leaving the nozzle and then, as a result of the grinding wheel's rotations with the rotational speed of n_s, delivered to the zone of contact between the grinding wheel and the hob cutter. The relationship in the form of multiple regression function was determined using the algorithm of the acceptance and rejection method. Next, on the basis of the equation, the evaluation of the impact of selected processing conditions (angle of nozzle ε and nominal emulsion expenditure $Q_{WET\text{-}IN}$) on the amount of emulsion reaching directly the grinding zone was performed.

2. Numerical tests of cooling and lubrication fluid flow during grinding of hob cutter blades

2.1. Conditions of supplying emulsion to the grinding zone

During grinding, the hob cutter fixed on the tool spindle moves together with the grinding table at the speed of v_w in relation to the grinding wheel rotating with speed n_s. The allowance a is removed in work cycles consisting of a grinding and return stroke, using grinding depth a_e.

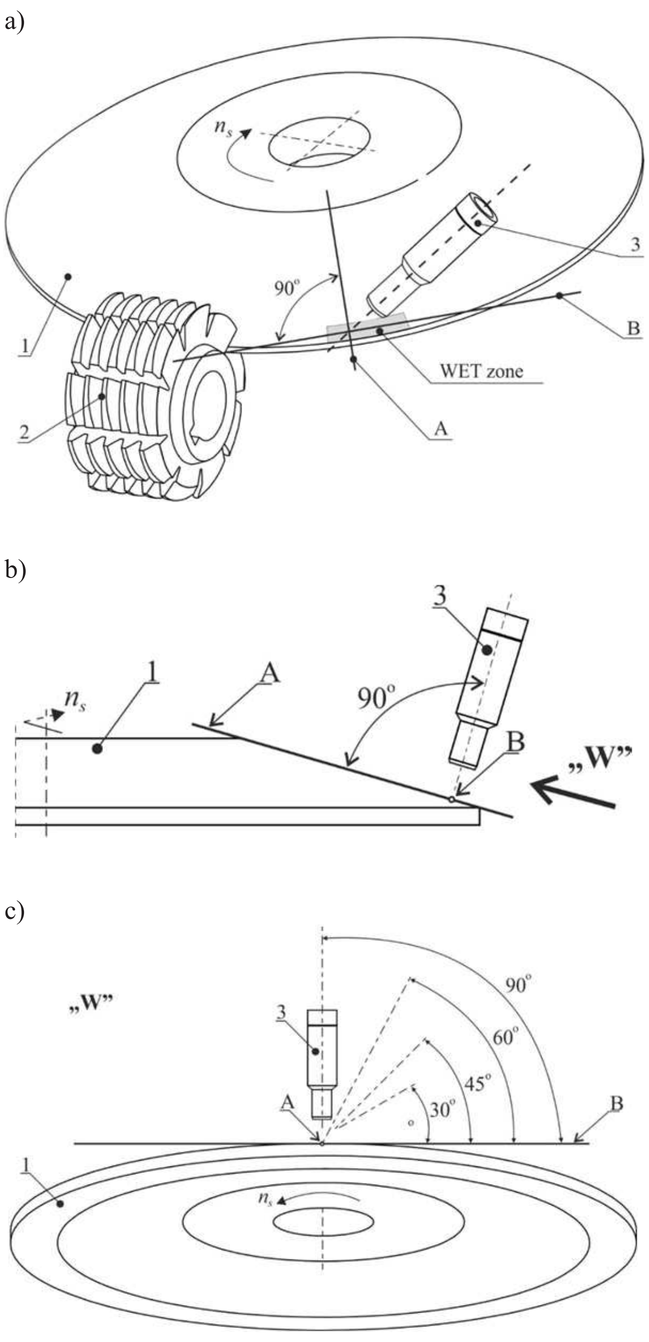

Fig. 1. The angular distribution of the nozzle relative to the grinding wheel active surface: a) general view, b) setting the nozzle against line A, c) setting the nozzle against line B; 1 – grinding wheel, 2 – hob cutter, 3 – nozzle, A – line determined by generatrix of the grinding wheel cone, B – line tangent to the grinding wheel active surface

It was assumed, that during the hob sharpening the grinding zone receives the cooling and lubricating fluid in the form of water oil emulsion based on Emulgol ES-12 oil (5%), through application of the flood method (WET). Figure 1 presents the placement of the WET area on the grinding wheel active surface onto which the emulsion stream is directed, as well as angular placement of the emulsion feeding nozzle in relation to the grinding wheel active surface.

As shown in Figure 1a, the water oil emulsion is introduced into the grinding zone by means of the nozzle *3* from the right side of the hob cutter *2* onto the fragment of active surface of the grinding wheel *1* designated as the "WET zone". This area is located as close as possible to the zone of contact between the grinding wheel and the hob cutter and its location takes into account the limitations introduced by mutual movement of the grinding wheel and the hob cutter during processing.

The axis of nozzle *3* is inclined towards the line A, determined by the generatrix of the grinding wheel cone, at an angle of 90º (Fig. 1b), and then at an angle ε in relation to the line B (Fig. 1c), tangential to the grinding wheel active surface and at the same time crossing the line A at an angle of 90º. As shown in Figure 1c, in the study there were applied four settings of angle ε, amounting accordingly to 30º, 45º, 60º and 90º. At the same time it is necessary to underline that the angular inclination of nozzle *3* in relation to line B cannot be less than 30°, which stems from technical limitations regarding nozzle alignment. Additionally, the outlet of nozzle *3* was located in the distance of 15 mm from the active surface of the grinding wheel. The grinding wheel, when rotating clockwise, lifts the emulsion and introduces it into the zone of contact between active abrasive grit and the hob cutter.

2.2. Numerical simulation of emulsion flow

Figure 2a show the 3D model of the system created for the purposes of numerical simulation. The systems consists of the following elements: grinding wheel, hob cutter, nozzle end and fluid domain. Table 1 shows the parameters of the hob cutter and grinding wheel that are necessary for creating their individual 3D models.

The next step after creating the 3D model of the system was the preparation and optimisation of computational grid within the whole fluid domain. Special emphasis was put on cohesion of the grid and appropriate compaction of the inflation layer at the location where the emulsion hits the surface of the rotating grinding wheel. The appearance of the fluid domain grid optimised for simulation purposes is shown in Figure 1b.

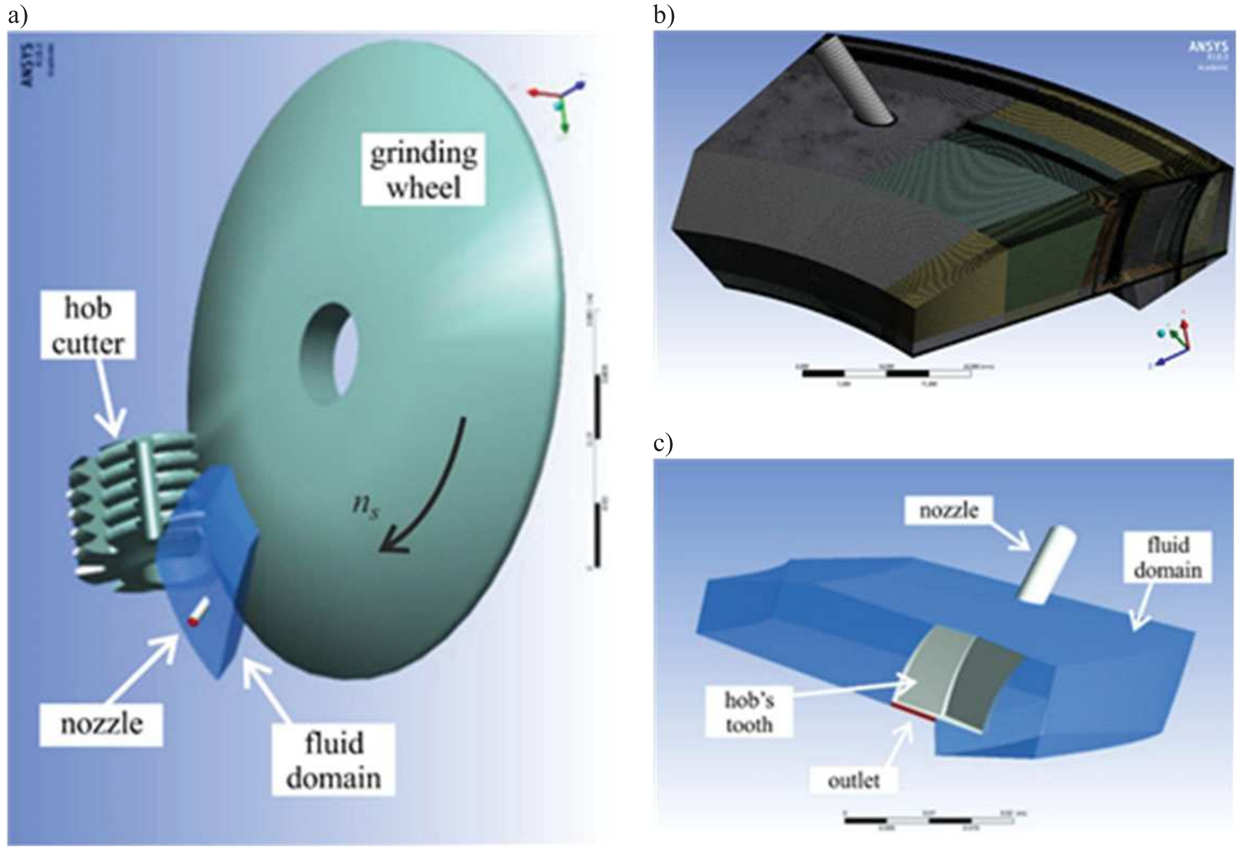

Fig. 2. 3D model of the system: grinding wheel – hob cutter – nozzle – fluid domain: a) general view, b) fluid domain grid, c) fluid domain outflow surface

Table 1.
Parameters of the hob cutter and the grinding wheel for the purposes of creation of 3D models

System element	Parameter
hob cutter	• symbol: NMFx-3/20°/B • module m=3 mm, • pressure angle α=20°, • number of cutting blades z_h=9, • ground profile, • accuracy class – B (according to PN-ISO 4468:1999).
grinding wheel	• type: 12 (according to PN-ISO 525:2001), • dimensions: 200/90×20/2×32 [11].

The numerical simulations for determining the efficient expenditure $Q_{WET\text{-}OUT}$ were conducted for twelve variants designated with the following variables:

- four angular locations of the nozzle, for the angle ε amounting accordingly to 30º, 45º, 60º and 90º,
- three nominal emulsion expenditures $Q_{WET\text{-}IN}$ at the inlet to the fluid domain, amounting accordingly to 3, 5 and 7 l/min.

It was assumed that the surface to be used for establishing what portion of the nominal expenditure $Q_{WET\text{-}IN}$ passes through the outlet surface from the fluid domain would be located under the hob cutter tooth indicated in Figure 1c.

The numerical simulations were carried out in the Ansys CFX software with the use of the "k-ω SST" turbulence model. The fluid domain was simulated as the interaction of two phases – emulsion phase and air phase. The phase parameters were defined as follows:

- air: ideal gas;
- emulsion: density: 960.7 kg/m^3, viscosity: 0.001488 Pa·s, nominal expenditure: 3, 5, 7 l/min.

2.3. Results of numerical simulations

Table 2 includes the results obtained from numerical simulations of emulsion flow. The graphical interpretation of Table 2 is shown in Figure 3.

Table 2.
Efficient expenditure $Q_{WET\text{-}OUT}$ in the grinding zone

Nominal expenditure $Q_{WET\text{-}IN}$, l/min	Nozzle inclination angle ε			
	30	45	60	90
	Efficient expenditure $Q_{WET\text{-}OUT}$, l/min			
3	0.828	0.630	0.390	0.375
5	1.145	1.025	0.600	0.450
7	1.596	1.106	0.805	0.441

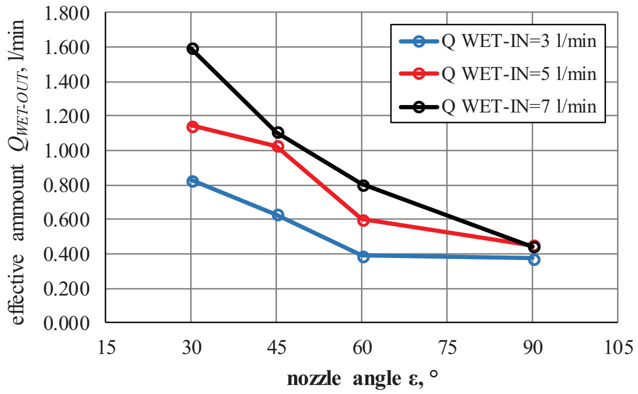

Fig. 3. Efficient expenditure $Q_{WET\text{-}OUT}$ obtained for four nozzle inclination angles ε – 90°, 60°, 45° and 30°, and three nominal expenditures $Q_{WET\text{-}IN}$ – 3 l/min, 5 l/min and 7 l/min

3. Determination of the mathematical relationship describing the impact of angle ε and nominal expenditure $Q_{WET\text{-}IN}$ on the efficient expenditure $Q_{WET\text{-}OUT}$

The SKZ software developed in the Institute of Machine Tools and Production Engineering of the Lodz University of Technology [12] was used for determining the mathematical relationship used for calculating the efficient expenditure $Q_{WET\text{-}OUT}$. The SKZ software enables determining the coefficients of the multiple regression equation. The procedure for regression analysis was developed on the basis of algorithm of the acceptance and rejection method described in paper [13].

The work with the software was started with introducing input data ($Q_{WET\text{-}IN}$, ε) from the previously prepared text file and choosing the form of the regression function (Y1 = B0 + Sum (Bi * Xi)).

The selection of the critical statistics values (F_{kr}) is made on the significance level of α=0.4 and after determining the regression function it is changed to the value of α=0.1. The calculations are started from the simplest regression function to which the new sections are subsequently added. When the newly added section reduces the significance of a section added earlier, the insignificant section is removed from the regression function. After introducing all the significant sections, the display shows a panel with preview of calculation results.

Finally, the function of the object of investigated took on the form shown below:

$$Q_{WET-OUT} = Q_0 \cdot Q_{WET-IN}^{f_Q} \cdot \varepsilon^{f_\varepsilon}, \tag{1}$$

where: $Q_{WET\text{-}IN}$ – [l/min]; ε – [°].

The values of constant and coefficient of this function determined on the basis of calculations are listed in Table 3.

Table 3.
Values of constant and coefficients for experimental function

Constant and coefficients	$Q_0 = 11.57$; $f_Q = 0.628$; $f_\varepsilon = -0.954$
Coefficient of multiple correlation R	0.967

After entering the numerical values from Table 3 into the function of the object of investigation (1) the following equation (2) was obtained:

$$Q_{WET-OUT} = 11.57 \cdot Q_{WET-IN}^{0.628} \cdot \varepsilon^{-0.954} \text{ [l/min]}. \tag{2}$$

4. Analysis and verification of the mathematical relationship obtained

The significance of the coefficients obtained for the multiple correlation R were determined by means of the Fisher-Snedecor F test through the calculation of the F coefficient test values and comparing them with the critical values F_{kr}. Because the calculations showed the relation $F > F_{kr}$, the correlation coefficients should be regarded as relevant, and this means the conformity (at the significance level of $\alpha=0.1$) of the regression equation with the investigation's results [14].

The graphical illustration presenting the impact of parameters ($Q_{WET\text{-}IN}$, ε) on the efficient expenditure $Q_{WET\text{-}OUT}$ is presented in Figure 4. The surface on the graph presents the level of value of efficient expenditure $Q_{WET\text{-}OUT}$ that is to be expected depending on the changing emulsion supply conditions.

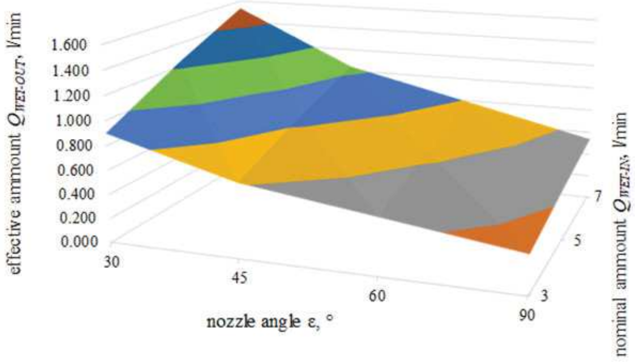

Fig. 4. Influence of nozzle inclination angle ε and nominal expenditure $Q_{WET\text{-}IN}$ on efficient expenditure $Q_{WET\text{-}OUT}$

As it stems from Figure 4 and dependency (2) with application at an angle of ε=90°, when the nozzle is positioned perpendicularly to the grinding wheel active surface, the values of $Q_{WET\text{-}OUT}$ for different nominal emulsion expenditures $Q_{WET\text{-}IN}$ are the lowest. A change in position of the nozzle as a result of inclining it by an angle ε results in the emulsion stream leaving the nozzle being directed toward the point of contact between the hob cutter and the grinding wheel, which, when combined with rotation of the grinding wheel, causes an increase in the amount of emulsion reaching the grinding zone. Thus, the lower the angle ε, the higher the efficiency of supplying the emulsion to the grinding zone, manifesting itself in greater efficient expenditure $Q_{WET\text{-}OUT}$. The highest efficiency of supplying the emulsion to the grinding zone was achieved when the nozzle was positioned at an angle of ε=30° and the nominal expenditure amounted to $Q_{WET\text{-}IN}$=7 l/min.

At the same time it can be noticed that together with decreasing the angle ε the impact of the amount of the nominal expenditure $Q_{WET\text{-}IN}$ on the obtained values of $Q_{WET\text{-}OUT}$ increases. This observation is confirmed by the values listed in Table 4.

In spite of the satisfactory values of the multiple correlation coefficient for the developed mathematical model, its verification was also carried out consisting of comparison the value of the efficient expenditure $Q_{WET\text{-}OUT}$ obtained from the numerical simulations with the values calculated on the basis of this model.

Figure 5 shows the comparison of calculated and simulated values of the efficient expenditure $Q_{WET\text{-}OUT}$ for the nominal expenditure $Q_{WET\text{-}IN}$ = 3 l/min (Fig. 5a), 5 l/min (Fig. 5b) and 7 l/min (Fig. 5c).

According to the analysis of the graphs presented in Figure 5, there are differences between the $Q_{WET\text{-}OUT}$ values obtained from simulation and those calculated on the basis of mathematical relationship. What draws attention is the fact, that on all the graphs the curves drawn on the basis of calculations run both above and below the curves drawn on the basis of numerical tests. The differences between them are minor, however. In case of supplying emulsion to the grinding zone with expenditure of 3 l/min (Fig. 5a), the greatest difference amounts to 0.074 l/min, which constitutes 2.5% of the $Q_{WET\text{-}IN}$ value. For the expenditure $Q_{WET\text{-}IN}$= 5 l/min (Fig. 5b) the greatest difference amounts to -0.183 l/min and constitutes 3.7% of value of the $Q_{WET\text{-}IN}$ expenditure, while for $Q_{WET\text{-}IN}$= 7 l/min (Fig. 5c) that difference takes the value of 0.096 l/min and constitutes only 1.4% of the initial expenditure value.

Table 4.
Efficient expenditure $Q_{WET\text{-}OUT}$ in the grinding zone – calculated values

Nominal expenditure $Q_{WET\text{-}IN}$, l/min	Nozzle inclination angle ε			
	30	45	60	90
	Efficient expenditure $Q_{WET\text{-}OUT}$, l/min			
3	0.899	0.611	0.464	0.315
5	1.239	0.842	0.640	0.434
7	1.534	1.040	0.790	0.537

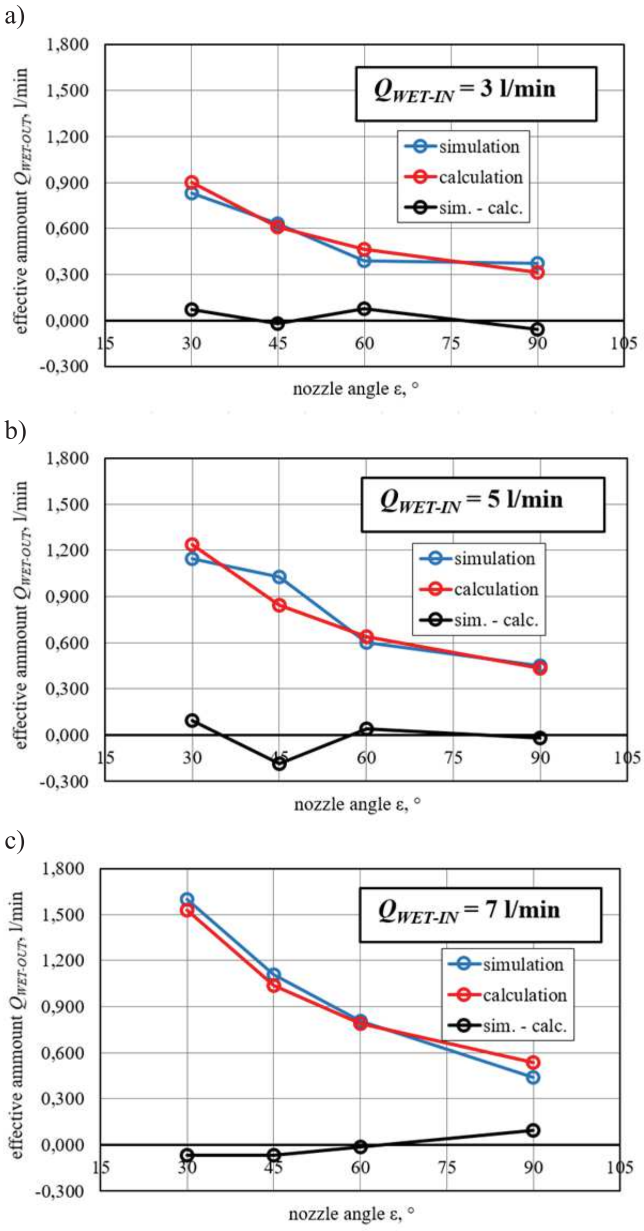

Fig. 5. Comparison of results of calculations and simulation of efficient expenditure $Q_{WET-OUT}$ for the nominal expenditure Q_{WET-IN}: a) 3 l/min, b) 5 l/min, c) 7 l/min

The above observations confirm the accuracy of the mathematical model developed.

5. Conclusions

The aim of this study was to evaluate the mathematical relationship enabling a prediction of the amount of emulsion reaching the grinding zone during the hob cutter sharpening. The possibility to predict the efficiency of supplying emulsion to the grinding zone is a relevant factor affecting the correct conducting of the hob cutter sharpening process. Based on an analysis of the obtained results obtained the following conclusions have been were drawn:

1. A mathematical model was elaborated in the form of multiple regression function that enables calculating the amount of efficient expenditure $Q_{WET-OUT}$ reaching directly the zone of contact between the grinding wheel and the hob rake at various nozzle angle setting and different initial expenditures of emulsion.
2. The acceptance and rejection method used for working out the model is relatively easy to apply and the verification of the relationship obtained confirmed its correctness.
3. The model developed creates a good basis for the analysis of the hob cutter sharpening process. Thanks to the determined mathematical relationship it is possible to avoid labour and time consuming experimental studies.
4. The highest efficiency of supplying the emulsion to the grinding zone was achieved when the nozzle was positioned at the lowest angle (ε=30°) with simultaneous application of the greatest nominal expenditure (Q_{WET-IN}=7 l/min).

References

[1] S. Kieraś, K. Nadolny, R. Wójcik, State in the art of cooling and lubrication of the machining zone in grinding processes, Mechanic 8-9 (2015) 204-211 (in Polish).

[2] G. Bianco, Materials used to manufacture hobs, Available from: www.biancogianfranco.com, Access in: 25.10.2018.

[3] www.lmt-tools.com, Access in: 25.10.2018.

[4] E. Brinksmeier, C. Heinzel, M. Wittmann, Friction, cooling and lubrication in grinding, CIRP Annals – Manufacturing Technology 48/2 (1999) 581-598.

[5] R.A. Irani, R.J. Bauer, A. Warkentin, A review of cutting fluid application in the grinding process, International Journal of Machine Tools & Manufacture 45 (2005) 1696-1705.

[6] S. Malkin, C. Guo, Grinding technology: Theory & application of machining with abrasives. Second Edition, Industrial Press Inc., New York, USA, 2008.

[7] W.B. Rowe, Principles of modern grinding technology. Second Edition, Elsevier, 2014.

[8] S. Ebbrell, N.H. Woolley, Y.D. Tridimas, D.R. Allanson, W.B. Rowe, The effects of cutting fluid application method on the grinding process, International Journal of Machine Tools & Manufacture, 40 (2000) 209-223.

[9] W. Stachurski, J. Sawicki, R. Wójcik, K. Nadolny, Influence of application of hybrid MQL-CCA method of applying coolant during hob cutter sharpening on cutting blade surface condition, Journal of Cleaner Production 171 (2018) 892-910.

[10] W. Stachurski, K. Nadolny, Influence of the condition of the surface layer of a hob cutter sharpened using the MQL-CCA hybrid method of coolant provision on its operational wear, International Journal of Advanced Manufacturing Technology 98 (2018) 2185-2200.

[11] NORTON.SAINT-GOBAIN Catalog 2017, Available from: www.saint-gobain-abrasives.com, Access in: 25.10.2018.

[12] B. Kruszyński, S. Midera, J. Kaczmarek, Forces in generating gear grinding-theoretical and experimental approach, CIRP Annals – Manufacturing Technology 47 (1998) 287-290.

[13] M. Cieciura, J. Zacharski, Probabilistic methods in practice, Vizja Press&IT, Warszawa, 2007 (in Polish).

[14] M. Korzyński, Methodology of the experiment - Planning, implementation and statistical analysis of the results of technological experiments, WNT, Warszawa, 2013 (in Polish).