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TESTS OF THE INNOVATIVE CONSTRUCTION OF THE GRAIN HAMMER MILL

Summary

The research procedures connected with the comparative study of the innovative design of the grain hammer mill at the time of barley's seeds crushing are presented in the study. For the purpose of the study's performance, there has been developed and constructed a test stand where the grain hammer mill differing in design of the hammer assembly – of rotor, was tested. The studies were conducted on the basis of the modern measurement apparatuses composed of a torque meter with a revolution counter MIR-20 and a two-channel measuring instrument MW2006-4 connected with a computer of IBM class. Recording of the values of the measured volumes was performed with the use of a PP203 software. Having conducted a statistical analysis of the results of the experimental studies it was found that the new design solution of the grain hammer mill's rotor was more effective than the standard one commonly used
***Key words**: grain hammer mill, crushing barley grains, the efficiency of crushing*

BADANIA INNOWACYJNEJ KONSTRUKCJI ROZDRABNIACZA BIJAKOWEGO

Streszczenie

W pracy przedstawiono postępowanie badawcze związane z badaniem porównawczym innowacyjnej konstrukcji rozdrabniacza bijakowego podczas rozdrabniania ziaren jęczmienia. Na potrzeby realizacji pracy opracowano i wykonano stanowisko badawcze, na którym badano rozdrabniacz bijakowy, różniący się konstrukcją zespołu bijakowego – wirnika. Badania prowadzono w oparciu o nowoczesną aparaturę pomiarową składającą się z momentomierza, z obrotomierzem MIR-20 oraz miernika dwukanałowego MW2006-4 połączonego z komputerem klasy IBM. Rejestracja wartości mierzonych wielkości realizowana była za pomocą programu PP203. Po dokonaniu statystycznej analizy wyników badań doświadczalnych stwierdzono, że nowe rozwiązanie konstrukcyjne wirnika rozdrabniacza bijakowego jest bardziej efektywne niż powszechnie stosowane standardowe rozwiązanie konstrukcyjne.
***Słowa kluczowe**: rozdrabniacz bijakowy, rozdrabnianie ziaren jęczmienia, efektywność rozdrabniania*

1. Introduction

Crushing of cereals' grains is one of the main technological operations realized in the agri-food industry and on farms. Out of many types of crushers, that is: radial plate grinding mills, roller mills, crushing mills and grain hammer mills, that are the grain hammer mills which, thanks to crushing efficiency, have found the widest use [1, 2, 5, 7, 12, 14].

The design solutions of grain hammer mills existing at present, are however characterized by high crushing energy consumption, as a result of what the power transmission systems of high powers have to be used for their power transmission [5, 9, 11, 14, 15, 16].

The purpose of the so far conducted studies concerning the grain hammer mills is to minimize the power outlays for realization of the crushing process, at simultaneous maintenance of high hammer mills's capacity [1, 2, 4, 6, 8, 10, 13]. Improvement of the already existing constructions or development of a completely new construction, and searching for optimum parameters of their work, constitute the foundation to obtain innovative design of beater shredders.

Due to that, conducting experimental tests of the grain hammer mills equipped with a traditional or a new construction of a rotor with hammers, and drawing up of its performance characteristics for barley grains' crushing, constitutes the purpose of the study.

2. The essence of the traditional and new construction of the grain hammer mill's rotor

A rotor with self-aligning or rigidly assembled hammers, the mill's screen or screens, a crushing plate or plates and the supporting structure with power transmission system are the essential elements of a typical grain hammer mill. Low capacity as compared to power consumption [2, 7] is the disadvantage and discomfort of well known, traditional design solutions of grain hammer mills. Most of all it is determined by the design of the rotor, where the hammers have the shape of rectangular plates. As the effect of that, under the influence of hammers' hits, the material's particles start to move on the near-circle paths. They make a thin layer rotating along the internal crushing chamber's circuit what causes, that in spite of sufficient degree of material's crushing material has been rotating there for quite a long time before it gets through the openings in the screens (of angle of contact 360°). In Fig. 1 there is presented a traditional grain hammer mill's rotor in the isometric view.

The essence of the new construction lies in the fact, that a disk rotor mounted on the shaft on which self-aligning hammers are fastened, constitutes the working assembly of the crusher. The hammers have the shape of plates in the form of circular sector of the angle of flare of at least 35°, while the hammer's fastening hole is on the symmetry axis of the circular sector near its arc footing. Such a construc-

tion of the grain hammer mill's rotor shall cause that the particles of the crushed material, hit by hammers, do not move on the circular path and do not create a rotating ring, but they move approximately radially with reference to screens (of the angle of contact 360°) and strike them immediately. It results in quicker passing of the material through the openings in the screens.

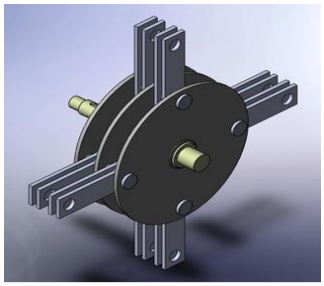

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Fig. 1. Isometric view of a grain hammer mill 's traditional rotor with rectangular hammers (α=0°), designed in Solid Works programme
Rys. 1. Widok izometryczny tradycyjnego wirnika rozdrabniacza bijakowego z bijakami prostokątnymi (α=0°), zaprojektowany w programie Solid Works

In Fig. 2 there is shown a new design of a rotor of the grain hammer mill in isometric view. The presented new design solution of the grain hammer mill's rotor is the subject matter of the patent RP no 173497 (Bochat A.).

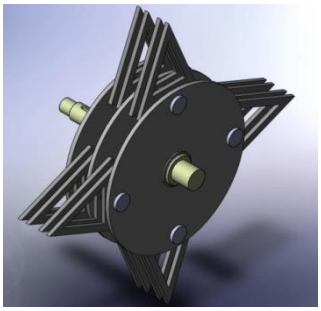

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Fig. 2. The isometric view of the new design of the grain hammer mill's rotor with hammers in the shape of a circular sector (α=45°), designed in Solid Works programme
Rys. 2. Widok izometryczny nowej konstrukcji wirnika rozdrabniacza bijakowego z bijakami w kształcie wycinka kołowego (α=45°), zaprojektowany w programie Solid Works

3. Plan and programme of experimental studies

In order to conduct the experiment, there has been accepted the plan and programme of the studies which assumes correlation between the independent variables and dependent variables.

As the independent variables in the experiment there have been assumed:
- angle of the hammers α […°],
- value of the hammer gap s [mm],
- diameter of openings in screens d [mm],
- peripheral speed of the hammers' endings v [m s^{-1}].

Where as the dependent variable determining the performance of the crushing process there have been assumed:
- crusher's capacity W_{JE} [kg s^{-1}],
- unit power consumption E_{rJE} [kJ kg^{-1}],
- share of individual fractions in the crushed material X [%].

As the fixed factors there have been assumed:
- relative air humidity w [%],
- air temperature t [°C].

The experiment has been conducted in the constant environmental conditions at the average ambient temperature 22,4°C and the average air humidity 45,6%.

Within the framework of the experiment, grains of properties presented in tab. 1 were crushed. That material was used for the studies due to the universality of crops and its designation for fodder purposes.

Table 1. Basic physical properties of the crushed material
Tab. 1. Podstawowe właściwości fizyczne rozdrabnianego materiału

No.	Grain's features	Unit	Characteristics
			Mean value
1.	Cereal's type	-	Barley
2.	Cereal's variety	-	Jare Antek
3.	Lenght	[mm]	9,57
4.	Width	[mm]	3,62
5.	Thickness	[mm]	2,59
6.	Substitutive diameter	[mm]	3,85
7.	Bulk density	[kg/m^3]	641,05
8.	Mass density	[kg/m^3]	717,85
9.	Relative humidity	[%]	12,68

Source: own work / Źródło: opracowanie własne

The experimental studies were planned for four design solutions of the grain hammer mill's rotor, three values of the hammer's gap, two values of opening diameters in screens and five values of peripheral speed of the hammer' ends. The values of these dimensions are presented in tab. 2.

Table 2. Specification of the independent variables' values
Tab. 2. Zestawienie wartości zmiennych niezależnych

		Independent variables' values				
		x_1	x_2	x_3	x_4	x_5
Independent variables	α [...°]	0	35	45	55	
	s [mm]	10	15	20		
	d [mm]	3	5			
	v [ms^{-1}]	38	45	52	59	66

Source: own work / Źródło: opracowanie własne

The experiment was planned according to the four-factor cross-classification type 4x(3x2x5), using 6 replicates in a test.

4. Methodology of the studies

For the purpose of the research, there has been designed and constructed a test stand which in a view is presented in Fig. 3.

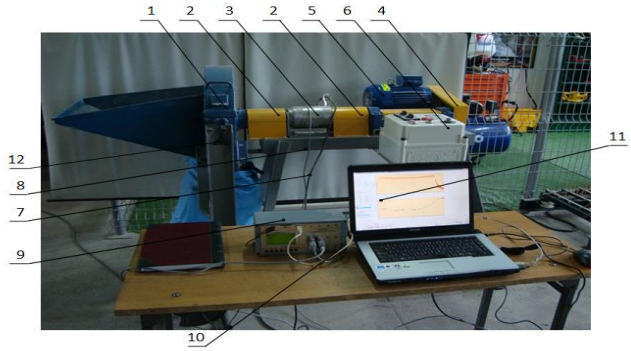

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Fig. 3. View of the test stand: 1- a modified grain hammer mill type WIR RB-1.3, 2- an elastic jaw clutch Poly-Norm, 3- torque meter with a revolution counter type MIR 20, 4- belt transmission, 5- electric motor 7 kW, 380 V, 6- control box with frequency converter Lenze SMD, 7- transmission conductor of the turning moment, 8- transmission conductor of the rotational speed, 9- two-channel meter MW2006-4, 10- transmission conductor type USB, 11- computer system with programme for data registering PP203 and the author's calculating programme RB01, 12- supporting structure

Rys. 3. Widok stanowiska badawczego: 1- zmodyfikowany rozdrabniacz bijakowy typu WIR RB-1.3, 2- sprzęgło kłowe elastyczne Poly-Norm, 3- momentomierz z obrotomierzem typu MIR 20, 4- przekładnia pasowa, 5- silnik elektryczny 7 kW, 380 V, 6- skrzynka sterownicza wraz z przetwornikiem częstotliwości Lenze SMD, 7- przewód transmisyjny momentu obrotowego, 8- przewód transmisyjny prędkości obrotowej, 9- miernik dwukanałowy MW2006-4, 10- przewód transmisyjny typu USB, 11- system komputerowy z programem do rejestracji danych PP203 oraz autorski program obliczeniowy RB01, 12- konstrukcja wsporcza

A modified grain hammer mill type WIR RB-1.3, equipped during the tests with a traditional working assembly or new prototype rotor's constructions was the object of the experimental tests, the technical data of the grain hammer mill are presented in the tab. 3.

Table 3. Technical data of the grain hammer mill WiR RB-1.3

Tab. 3. Dane techniczne rozdrabniacza WiR RB-1.3

Technical data	**Value**	**Unit**
Maximum number of the crusher's rotor revolutions	3000	[rev./min]
Number of hammers	16	[pcs.]
Number of replaceable screens	2	[pcs.]
Dimensions of holes in the screens	3; 5	[mm]
Width of the screens	106	[mm]
Diameter of the rotor with hammers:		
for a hammer's gap equal to 20 mm	414	[mm]
for a hammer's gap equal to 15 mm	424	[mm]
for a hammer's gap equal to 5 mm	434	[mm]
Marking of the electric motor	Sg112M4	-
Maximum number of engine's revolutions	1455	[rev./min]
Motor's power	7	[kW]

Source: own work / Źródło: opracowanie własne

In order to conduct the experiment, the following measurement methods have been used within the scope of barley's crushing:

1. Measurement of humidity and air temperature in the laboratory was executed with the use of a measuring device HUMIPORT 10.
2. Measurements of humidity and temperature of samples of cereals to be crushed was executed with the use of a halogen humidity analyzer HR83.
3. Measurement of bulk density of the examined cereals' grains was performed with the use of a densimeter WGILAB – RDW – 143.
4. Measurement of the turning moment on the rotor's shaft and the shaft's rotational speed was carried out with the use of a torque meter with revolution counter type MIR 20, which was connected with the two-channel measuring device MW2006-4.
5. Measurement of the grain samples' mass before and after crushing was performed with the use of a platform scale Axis B15.
6. In order to determine the percentage share of crushed grains' fractions, samples of the mass of 100 g for each replicate in the analyzed test point. Then the screen analysis with the use of a laboratory shaker LPZE-0 was conducted in accordance with the Polish Standard PN-R-64798.

5. Analysis of the tests results

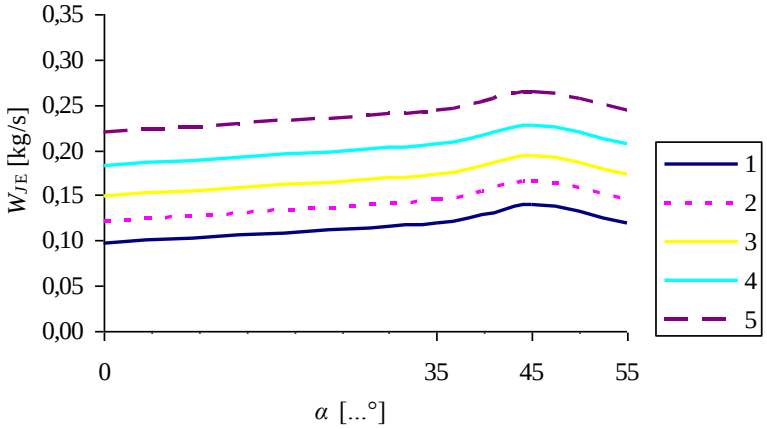
5.1. Capacity of the grain hammer mill

As a result of conducting of the multidimensional regression analysis, a formula considering the impact of independent variables on the capacity of a grain hammer mill at the time of barley's grains crushing was obtained:

$$W_{JE} = (-2{,}55\cdot 10^{-1}) - (7{,}15\cdot 10^{-3})\alpha + (1{,}54\cdot 10^{-2})s + (3{,}65\cdot 10^{-2})d + (3{,}74\cdot 10^{-4})\alpha^2 - + (5{,}48\cdot 10^{-4})s^2 + (4{,}25\cdot 10^{-5})v^2 - (4{,}30\cdot 10^{-6})\alpha^3. \quad (1)$$

From the developed multidimensional regression equation (1) it results, that all the independent variables specified in the tests programme exert an essential impact on the capacity of a crusher at the time of barley's seeds crushing. The analysis of regression was conducted on the level of significance $\alpha_{gr} = 0{,}05$, the correlation coefficient of multivariate was $R^2 = 0{,}96$.

In Fig. 4 there are presented exemplary characteristics of the crusher's capacity at the time of barley's crushing for four different values of the hammers' angles α, peripheral speeds of the hammer's endings v and the selected value of the hammer's gap s as well as for two values of openings' diameters in the crusher's screens d. From the presented characteristics of the multidimensional regression it results, that the hammers in the form of a circular sector of the angle α=45° have the highest crushing capacity, while the lowest capacity characterizes the rectangular hammers α=0°.



No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	S [mm]	d [mm]
1.	0	38	2.	0	45	3.	0	52	4.	0	59	5.	0	66	15	5
	35	38		35	45		35	52		35	59		35	66		
	45	38		45	45		45	52		45	59		45	66		
	55	38		55	45		55	52		55	59		55	66		

Source: own work / Źródło: opracowanie własne

Fig. 4. Impact of the hammers' angle on the capacity of a grain hammer mill at the time of barley's seeds crushing for the value of the peripheral speeds of the beaters' endings *v*, the hammer's gap *s*=15 mm and the diameter of openings diameters in screens *d*=5 mm
Rys. 4. Wpływ kąta bijaków na wydajność rozdrabniacza bijakowego podczas rozdrabniania jęczmienia dla wartości prędkości obwodowych końców bijaków v, szczeliny bijakowej s=15 mm i średnicy otworów w sitach d=5 mm

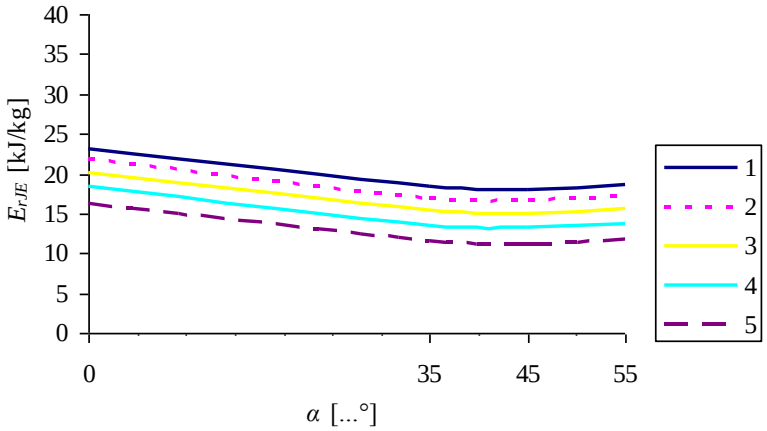
5.2. The unit power consumption for crushing

As a result of conducting the multidimensional regression analysis, the formula considering the impact of independent variables on the unit power consumption at the time of crushing has been received:

$$E_{rJE} = (3{,}62 \cdot 10^{1}) - (1{,}75 \cdot 10^{-1})\alpha + 3{,}96\,s - 7{,}40\,d - (1{,}42 \cdot 10^{-1})s^2 - + (2{,}35 \cdot 10^{-3})v^2 + (3{,}00 \cdot 10^{-5})\alpha^3 . \quad (2)$$

From the drawn up multidimensional regression equation (2) it results, that all the independent variables determined in the tests programme, exert an essential impact on the unit power consumption at the time of barley crushing. The regression analysis was conducted on the level of significance $\alpha_{gr} = 0{,}05$, the correlation coefficient of multivariate was $R^2 = 0{,}93$.

In Fig. 5 there are shown exemplary characteristics of the unit energy consumption at the time of barley's **crushing** depending on the hammers' angles *α* as well as for peripheral speed of the hammers' endings *v* for the selected values of a hammer gap *s* and the diameter of openings in the crushers' screens *d* assumed in the tests plan.



No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	No.	α [...°]	v [m/s]	s [mm]	d [mm]
1.	0	38	2.	0	45	3.	0	52	4.	0	59	5.	0	66	15	5
	35	38		35	45		35	52		35	59		35	66		
	45	38		45	45		45	52		45	59		45	66		
	55	38		55	45		55	52		55	59		55	66		

Source: own work / Źródło: opracowanie własne

Fig. 5. Impact of the hammers' angle on the unit energy consumption at the time of barley's crushing for the values of the peripheral speeds of the hammers' endings *v*, the hammer gap *s*=15 mm and the diameter of openings in screens *d*=5 mm
Rys. 5. Wpływ kąta bijaków na jednostkowe zużycie energii podczas rozdrabniania jęczmienia dla wartości prędkości obwodowych końców bijaków v, szczeliny bijakowej s=15 mm i średnicy otworów w sitach d=5 mm

The unit energy consumption at the time of barley's crushing is of the polynomial function's character and reaches the lowest value for the rotor equipped with hammers in the shape of a circular sector α=45°, while the biggest value it reaches in case of the use of a rotor with rectangular hammers α=0°. The tendency of changes of the developed function of the multidimensional regression is similar for each value of the hammer gap *s* as well as for the diameter of openings in the screens *d*, while the differences occur only in individual values of the unit energy consumption.

5.3. The percentage share of crushed fractions

Formulas considering the impact of independent variables on the fractions' contents at the time of barley's crushing were obtained as a result of conducting the multidimensional regression analysis:

- for dusty fraction:

$$X_{1JE} = (4{,}91\cdot10^{-1}) + (8{,}71\cdot10^{-3})\alpha - (1{,}76\cdot10^{-2})s - (4{,}22\cdot10^{-2})d^2 - (4{,}65\cdot10^{-4})\alpha^2 + (7{,}18\cdot10^{-4})s^2 + (3{,}22\cdot10^{-5})v^2 + (5{,}19\cdot10^{-6})\alpha^3. \quad (3)$$

- for fine fraction:

$$X_{2JE} = (3{,}88\cdot10^{-1}) + (1{,}82\cdot10^{-2})\alpha + (1{,}78\cdot10^{-2})s - (3{,}76\cdot10^{-2})d^2 - (9{,}32\cdot10^{-4})\alpha^2 - + (4{,}41\cdot10^{-4})s^2 + (1{,}08\cdot10^{-5})\alpha^3 + (4{,}97\cdot10^{-7})v^3. \quad (4)$$

- for coarse fraction:

$$X_{3JE} = (1{,}53\cdot10^{-1}) - (2{,}69\cdot10^{-2})\alpha + (7{,}98\cdot10^{-2})d^2 + (1{,}40\cdot10^{-3})\alpha^2 - + (2{,}85\cdot10^{-4})s^2 - (1{,}60\cdot10^{-5})\alpha^3 - (8{,}96\cdot10^{-7})v^3. \quad (5)$$

From the developed equations of multidimensional analysis (3), (4) and (5) it results, that all the independent variables determined in the tests programme exert an essential impact on the share of individual fractions at the time of barley's crushing. The analysis of regression was conducted on the significance level α_{gr}=0,05, and the correlation coefficients of multivariate R^2 for equations (3), (4) and (5) were respectively: R^2 = 0,97; 0,94; 0,98.

In the tab. 4 there are presented the values of independent variables for which the values of dependent variables were the lowest and the highest. These values have been collected on the basis of the multidimensional regression's equations presented in the study.

6. Conclusions

1. It results from the conducted experimental studies that an essential impact on the crusher's output and on the unit energy consumption and the content of fractions in the crushed barley's grains exert:
- construction form of the hammer's assembly,
- the hammers' angle,
- peripheral speed of the hammers' endings,
- openings' diameter in screens,
- the hammers' gap.

2. Application of a new design of a rotor equipped with hammers in a shape of a circular sector in a grain hammer mill resulted in the increase in a crusher's output from 11 to 32% and the decrease in consumption of the unit energy for crushing from 14 to 46% (in the extreme) – as compared to the traditional design solution of a rotor.

3. Application of a new construction of a grain hammer mill's rotor equipped with hammers in the shape of a circular sector results in the decrease in the dusty fraction of crushed cereals as compared to the traditional construction solution. Application of hammers of the angle α=45° has an impact on:
- decrease in the content of dusty fraction from 7,26 to 7,75%,
- decrease in the content of fine fraction from 8,58 to 9,23%,
- increase in the content of coarse fraction from 16,33 to 16,49%.

4. The conducted assessment of crushing efficiency proved, that in case of barley's crushing, the most effective construction solution of the hammer's assembly is the use of hammers in the shape of circular sector α=45°, a hammer gap of the value of *s*=10 mm and screens of the openings' diameter *d*=5 mm.

Table 4. Specification of the dependent and independent variables' values
Tab. 4. Zestawienie wartości zmiennych zależnych i niezależnych

Dependent variable			Crushed material	Independent variable			
Symbol of variable	Name of the variable	Value of the variable		Hammers' angle α [...°]	Value of hammer's gap *s* [mm]	Diameter of openings in screens *d* [mm]	Peripheral speed if the hammers' endings *v* [m⊙s^{-1}]
W_{JE}	Crushers capacity	max	Barley	45	15	5	66
W_{JE}	Crushers capacity	min	Barley	0	20	3	38
E_{rJE}	Unit crushing energy	min	Barley	45	20	5	66
E_{rJE}	Unit crushing energy	max	Barley	0	10	3	38
X_{1JE}	Share of dusty fraction	min	Barley	45	10	5	38
X_{1JE}	Share of dusty fraction	max	Barley	0	15	3	66
X_{2JE}	Share of fine fraction	max	Barley	0	20	3	66
X_{2JE}	Share of fine fraction	min	Barley	45	10	5	38
X_{3JE}	Share of coarse fraction	max	Barley	45	10	5	38
X_{3JE}	Share of coarse fraction	min	Barley	0	20	3	66

Source: own work / Źródło: opracowanie własne

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