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OPTIMIZED MATHEMATICAL MODEL OF A GRAIN CLEANING SYSTEM FUNCTIONING IN A COMBINE HARVESTER USING RESPONSE SURFACE METHODOLOGY

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The performance of grain combine harvesters is determined by three factors: threshing power, losses and fuel consumption. Loss can be reduced by separating processes and providing a suitable mathematical model for each of them by examining and measuring the factors influencing loss and optimizing their function. This model is then to be used for the purposes of controlling the system. An important process that has a significant impact on combine loss is the cleaning system. This study modelled and optimized the function of a cleaning system using response surface methodology (RSM). Feed rate, fan speed, and upper sieve opening were considered independent variables; the percentage of grain passage, content of materials-other-than-grains (MOG), and semi threshed cluster (s.t.c.) passing through the upper sieve were viewed as dependent variables. The results showed a significant effect of all three independent variables on the percentage of free grains with a probability level of 0.01. However, not all interactions were significant. Moreover, it was found that only mechanical factors had a significant effect on the percentage of s.t.c. passing, while fan speed and all interactions showed no significant effect. All three independent variables significantly affected the MOG content passing. An appropriate exponential model was found for all three dependent variables. Subsequently, the optimal conditions were determined for the maximum passage of free grains through the upper sieve and the minimum MOG at 3.33 $kg \cdot s^{-1}$ feed rate, 742 rpm fan speed, and an upper sieve with 10 mm openings with a desirability of 0.84, based on RSM modelling.

Keywords: loss; performance; optimization; RSM; MOG

Cereal crops are harvested mostly by grain combine harvesters. The employment of combine harvesters is becoming a successful solution to conquer the shortage of labour for harvesting grain in world (Mokhtor et al., 2020). The performance of grain combine harvesters is determined by three factors: threshing power, losses, and fuel consumption (Hunt, 2001). Various factors affect wheat loss during harvest, including unregulated combine harvester, untimely harvest, combine type, seed type, the slope of fields, etc. (Mirzazadeh et al., 2015). An important process with a significant impact on overall combine loss is the cleaning, which is the last step of separating the grain from the MOG. The cleaning unit function can be evaluated in three ways:

1. grain quantity loss (these are divided into two categories: free grains and s.t.c.;
2. grain quality loss, such as MOG content in the grain bin (Benaseer et al., 2018);
3. working capacity of cleaning system (Srivastava et al., 2006).

The cleaning system function is affected by design factors, working conditions, crop conditions, and farming conditions. Researchers have used various models, such as experimental models, physical models, simulation models and statistical models, to identify these factors and how they affect the cleaning unit function (Badretdinov et al., 2019; Myhan and Jachimczyk, 2016). These models provided tools to simulate and optimize the process and its automatic control setting as a consequence. Most of these models were criticized for being unique, indicating that they were valid only under the specific conditions of the identical experiments. The researchers felt vacancy that provided a comprehensive mathematical model for explaining the cleaning system function. A comprehensive mathematical model has the following advantages:

1. comprehensive understanding of the basic relationships between physical processes;
2. quantification of the parameters of immeasurable dynamic processes;
3. efficient reduction of costs and experiment time;
4. accuracy prediction of the unit function over a wide range of parameter changes;
5. planning keys to simulate the dynamic process and optimize the design and operational parameters of the work unit;
6. calculation of components for the development of automatic control system of combine harvester to improve the overall function under farming operations;

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7. research tools to further improve the design and development of new units (Mirzazadeh et al., 2021; Miu and Kutzbach, 2008).

Voicu et al. (2007) presented a series of mathematical models for predicting the loss of upper sieve in grain harvesting combine and predicting the percentage of sifted material in conventional sieves by using π-Buckingham theorem and dimensional analysis. They proposed a mathematical model to predict the upper sieve loss of the combine harvester. Kutzbach (2003) conducted studies to increase the working capacity of the conventional combine harvester cleaning system. The results showed that the system cleaning capacity will increase if a circular oscillation (similar to that used in sieve movement) is used instead of the linear oscillating motion of the sieve. In order to automatically control the combine cleaning system, Craessaerts et al. (2007a, 2007b, 2008, 2010) attempted to use a variety of sensors applied to the combine harvester to investigate interactions and prioritize potential factors affecting the cleaning system performance such as fan speed, upper and lower sieve openings, feed rate, etc. Their studies showed that quality loss is mainly affected by two factors – fan speed and load on the upper sieve – and quantitative loss is mainly affected by pressure on the rear-left side of the upper sieve. Wallays et al. (2009) investigated the selection of a hyperspectral radio band based on a multispectral vision system for online measurement of qualitative loss of harvester cleaning system and separation of MOG from grain in the combine tank. Mirzazadeh et al. (2015) observed that the skewness of grain separation distribution diagrams along the upper sieve decreased with increasing feed rate and fan speed and decreasing the size of upper sieve opening. Furthermore, the kurtosis rate of graphs decreases with increasing feed rate and fan speed and decreasing the size of upper sieve opening. Liang et al. (2016) used an impact-type piezoelectric sensor developed for real-time monitoring in sieve of combine harvester cleaning system. The results showed successful application of this type of sensor for the purposes of loss control in the standard range. Šotnar et al. (2018) observed that proper knowledge and operator's skills with harvesting process is a complex issue necessary for reduction of harvest loss and, hence, increasing of economic yields, since the recommended settings are provided for average conditions that are not likely to occur. Mesri et al. (2019) also used RSM to determine the space between threshing drum and concave, fan speed, and sieve opening size as independent variables in order to optimize the dependent parameters. However, the mathematical model and interpretation of independent parameters on dependent variables are not considered here.

According to studies, great importance has been given to the effect of feed rate, fan speed, and upper sieve opening factors on grain percentage and the percentage of s.t.c passing through the upper sieve and grain loss, MOG content passing through the sieve openings, overloading of the upper sieve, and increasing the qualitative loss of mechanized wheat harvesting operations. Moreover, a review of previous studies confirms that RSM has not been used to investigate combine function and an appropriate mathematical model other than recent research has not been provided. Therefore, the main purpose of this study is to develop a model and optimize the independent variables (feed rate, fan speed, and upper sieve opening size) and dependent variables (grain percentage, MOG content, and percentage of s.t.c. passing through the upper sieve holes) using RSM.

Material and methods

To conduct the experiments, this study used the 68's Sahand combine harvester cleaning system. For these purposes, the main combine harvester chassis was prepared prior to mounting of necessary parts, including grain pan, upper sieve, and fan to the main chassis. An electromotor was used to move the grain pan and upper sieve and subsequently vibrate them. The inverter was used to create different revolutions for the electromotor and subsequently the fan. To measure the dependent variables, a grain pan measuring 102×160 cm^2 was designed and constructed. The pan was divided into two separate cells. The first cell with dimensions 102×140 cm^2 served for measurement of the percentage of material passing through, including free grain percentage, MOG content, and the percentage of s.t.c. through the upper sieve holes. The second cell, with dimensions 102×20 cm^2, was for measuring the amount of material not passed. To prevent the free wind movement created by the fan, they were made of mesh by pan walls, lateral walls, and inner walls. The test pan was then placed just below the upper sieve (Fig. 1). Laboratory sampling was performed from the farms of the Iranian Dryland Research Organization, Maragheh. To optimally simulate the experiments with farming operations, laboratory

Fig. 1 Combine harvester cleaning unit used in research included main chassis of the 68's Sahand combine harvester, agricultural tiller, upper sieve, grain pan, electromotor and inverter

samples were taken from the same type of combine (68's Sahand) in operation. In first, the upper and lower sieves of the combine were removed, and the fan was completely disabled. Then, experimental plots (10 metres long and 81 metres wide) were established at the field. During the harvesting and sampling, all combine harvester settings (driving speed, clearance ratio and rotational speed of the threshing cylinder, reel speed (based on skilled operator's opinion)) were set. Subsequently, all harvested material was transferred into plastic bags to preserve the material moisture content. Finally, the material was transported and stored at the test site. Independent variables in these experiments were feed rate (A) at three levels (1.56, 1.93, and 2.33 kg·s^{-1}); fan speed (B) at three levels (450, 600, and 750 rpm); upper sieve opening size (C) at three levels (6, 8, and 10 mm). The percentage of free grain passage (Free Grain Passing), MOG content passage (MOG Passing), and the percentage of semi threshed cluster passing through the upper sieve (S.T.C. Passing) were considered dependent variables and were calculated as follows:

$$\textit{free grain passing}\ (\%) = \frac{A-B}{T} \times 100\% \tag{1}$$

$$\textit{MOG passing}\ (\%) = \frac{C}{T} \times 100\% \tag{2}$$

$$\textit{S.T.C passing}\ (\%) = \frac{D-E}{T} \times 100\% \tag{3}$$

where:
A – total amount of free grains fed to the grain pan; *B* – free grain percentage of the last cell; *C* – MOG content passage of the upper sieve openings; *D* – total amount of s.t.c. fed to the grain pan; *E* – total amount of s.t.c. of the last cell; *T* – total amount of nutrients fed, including materials containing grain and MOG

The experiments were performed as a factorial pattern based on a completely randomized block design in three iterations (Valizadeh and Moghaddam, 2011). After each experiment, the material passing through the upper sieve openings was emptied and poured into each cell into small plastic bags. Subsequently, the passing material was separated and weighed. At this stage, the material inside the bags was separated into its constituents, free grains, s.t.c. and MOG and then weighed and recorded by a digital scale with a sensitivity of 0.01 g.

The obtained data were analysed by Design Expert 12 software (Minneapolis, USA, Stat-Ease Inc.). Utilizing this method, the desired level is affected by independent variables, and the goal is to optimize the response. The optimal value (y_k) was determined by solving the regression equation (Golpour et al., 2020; Olawale et al., 2020):

$$y_k = \beta_0 + \beta_1^{\sum_{j=1}^{k}\beta_j x_j + \sum_{j=1}^{k}\beta_{jj} x_j^2 + \sum\sum_{i<j}^{k}\beta_{ij} x_i x_j} \tag{4}$$

where:
β_0, β_1, β_j, β_{jj}, β_{ij} – parameters of the regression coefficients; x_j, x_i – input coded variables

Attempts were conducted to fit the response levels and optimize the material separation process using Design Expert 12 software by solving multiple regression equation (Eq. 4). Mathematical models for each response were evaluated by multiple linear regression analysis. Statistical significance of independent variables on response variables was investigated at a 95% confidence level (P <0.05). In the proposed regression equation, only variables with a significant effect on the response variable were used. Finally, the optimal point of the process was determined according to the boundary conditions and objective functions (Table 1). As it can be seen, due to the importance of 'feed rate' factor among independent variables – due to its role in field capacity – and 'grain and MOG passing' factors among dependent variables – due to their roles in losses – their values were 5 and the rest were 3 due to their low importance.

Results and discussion

Table 2 presents ANOVA results of materials passing through the upper sieve, including Free Grain Passing, MOG Passing, and S.T.C. Passing through the upper sieve. Different models were also proposed and evaluated to determine the relationship between feed rate, fan speed, and upper sieve opening size variables and dependent variables. The results are presented in Table 3.

Percentage of free grain passing

According to Table 2, all three independent variables significantly affected the percentage of Free Grain Passing through the upper sieve with a probability level of 0.01; however, not all interactions were significant. Therefore, this study discusses the effect of independent variables on the percentage of Free Grain Passing. Different models were also measured and evaluated to determine the relationship between the independent variables and the percentage of

Table 1 Boundary conditions of independent and dependent variables

Variables	Goal	Lower limit	Upper limit	Importance
Feed rate (kg·s^{-1})	maximize	1.56	3.33	5
Fan speed (rpm)	in rang	450	750	3
Upper sieve opening (mm)	in rang	6	10	3
Free Grain Passing (%)	maximize			5
S.T.C. Passing (%)	maximize			5
MOG Passing (%)	minimize			3

Table 2 ANOVA of independent factors effect on dependent variables

Source	df	Mean square	*F*-value	Mean square	*F*-value	Mean square	*F*-value
		free grain passing		S.T.C passing		MOG passing	
Model	9	11.71	29.07**	0.44	100.89**	45.30	32.65**
A-Feed rate	1	25.51	63.35**	0.06	14.32**	14.62	10.54**
B-Fan speed	1	34.64	86.00**	0.003	0.67^{ns}	222.82	160.62**
C-Sieve opening size	1	39.01	96.87**	3.84	880.3**	141.18	101.77**
AB	1	0.16	0.4^{ns}	0.008	1.96^{ns}	0.0217	0.016^{ns}
AC	1	0.60	1.50^{ns}	0.008	1.96^{ns}	0.1976	0.14^{ns}
BC	1	0.088	0.22^{ns}	0.005	1.20^{ns}	3.26	2.35^{ns}
A^2	1	3.54	8.79**	0.011	2.45^{ns}	1.85	1.33^{ns}
B^2	1	0.003	0.007^{ns}	0.022	5.05*	0.0480	0.035^{ns}
C^2	1	1.79	4.45*	0.0003	0.072^{ns}	23.69	17.08**
Residual	17	0.403		0.004		1.39	

Table 3 Proposed fitted mathematical models using the RSM for dependent variables

Dependent variables	Equation	Eq. number	R^2	Adj R^2	Pred R^2
Grain passing	$y_1 = 50 + 34.4e^{(-1.9A - 0.0009B + 0.3C + 0.42A^2 - 0.01C^2)}$	5	0.94	0.93	0.90
S.T.C passing	$y_2 = 1 + 0.05e^{(-0.014A + 0.59C - 0.023C^2)}$	6	0.97	0.97	0.96
MOG passing	$y_3 = 5 + 1.88e^{(0.15A - 0.001B + 0.61C - 0.03C^2)}$	7	0.94	0.93	0.91

materials containing grain. Finally, based on the results of regression of these models (Table 2), quadratic exponential model with R^2 = 0.94 was found appropriate (Eq. 5). The significance of main effects indicated the efficiency of mechanical and pneumatic methods in separating grain from other materials and increasing its passage through the openings of the upper sieve, and consequently, reducing grain loss in the upper sieve. Based on the diagrams (Fig. 2), the Free Grain Passing percentage decreases exponentially with the quadratic power with increasing feed rate, which can be attributed to the reduced possibility of grain penetration into the thickened layer of material as one of the important reasons. As the feed rate increases, the probability of grain penetration and movement among other materials decreases, leading to an increase in the time taken for the grain to reach the sieve surface and pass through its openings, leading to a decrease in the percentage of grains passing through the upper sieve openings, and consequently, an increase in grain loss in the upper sieve rear. Examination of Eq. 5 and Fig. 2 shows that the Free Grain Passing percentage decreases exponentially with a linear view with increasing fan speed. The reduced grain rate at high fan speeds can be attributed to further material transfer, including grain transfer to the sieve, resulting in grain loss increasing in the rear part of the upper sieve increase (Miu and Kutzbach, 2008; Craessaerts et al., 2008, 2010).

Based on Eq. 5, the Free Grain Passing percentage increases exponentially with the quadratic power with increasing sieve opening size due to improved possibility of grain passing that have reached the sieve surface. The air velocity also decreases due to the increasing passage cross-sectional area at a constant fluid flow rate – as the upper sieve opening size increases, the rate of material

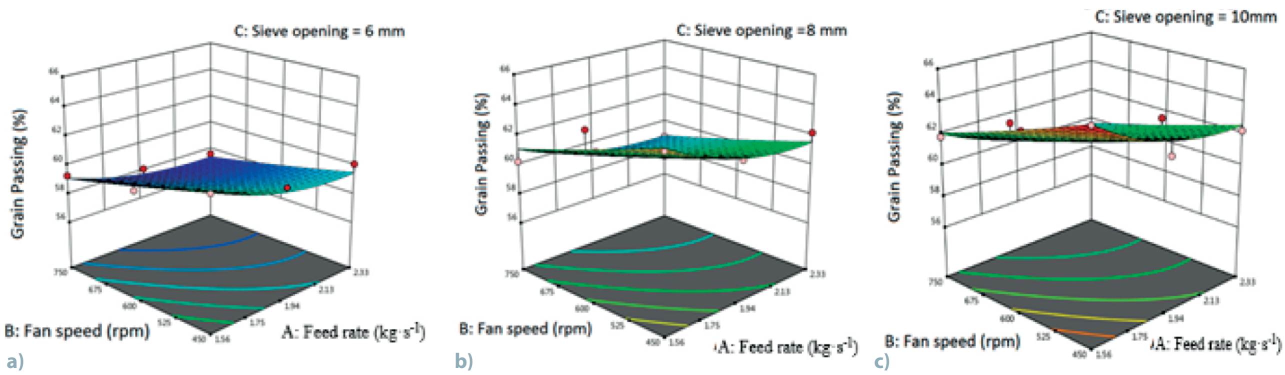

Fig. 2 3D diagram of impacts of material feed rate and fan speed on Free Grain Passing through the sieve with different opening sizes: a) 6 mm, b) 8 mm, and c) 10 mm

transfer, including grain, to the upper sieve rear decreases, and consequently, the time that the grains stay on the sieve increases, leading to an increase in the rate of grain passage from the upper sieve and a decrease in loss in its rear part.

The amount of S.T.C. passing

According to Table 2, feed rate and upper sieve opening size have a significant effect on the S.T.C. Passing, at probability levels of 0.05 and 0.001, while the fan speed and all interactions have an insignificant effect. The insignificant effect of fan speed can be attributed to the terminal velocity of s.t.c, indicating a higher importance of mechanical factors than pneumatic factors in separating s.t.c. from other materials and their higher passage through the upper sieve. This study evaluated various models to determine the relationship between independent variables and the amount of s.t.c. Finally, the exponential model, which utilizes significant variables, was found to be appropriate. (Eq. 6). Additionally, the high coefficient of determination of this model (R^2 = 0.97) indicates that the independent variables can justify most of the changes in the dependent variables. Based on Fig. 3, the S.T.C. Passing amount imperceptibly decreases with increasing feed rate due to the reduced probability of penetration of s.t.c. to other materials and its difficult separation at high feed rates. Increased feed rate leads to an increase in material layer thickness on the sieve. Hence, it becomes more difficult for s.t.c to penetrate and reach the sieve surface. Figure 3 also shows the effect of sieve opening size on the S.T.C. Passing percentage – the s.t.c percentage naturally increases significantly with increasing opening size due to the increased probability of s.t.c. passing by penetrating into other materials and thus delivering them to the sieve surface. In this case, the probability of rapid passage of s.t.c. through the upper sieve increases with increasing sieve opening size, accompanied by an increase in the cross-sectional area of the sieve opening. This leads to reduction in the s.t.c. loss in the upper sieve. Finally, it was found that fan speed had no significant effect on the S.T.C. Passing. This can be attributed to the terminal velocity of s.t.c. Furthermore, it indicates the higher importance of mechanical factors than pneumatic factors in s.t.c. separating from other materials and its passage through the upper sieve.

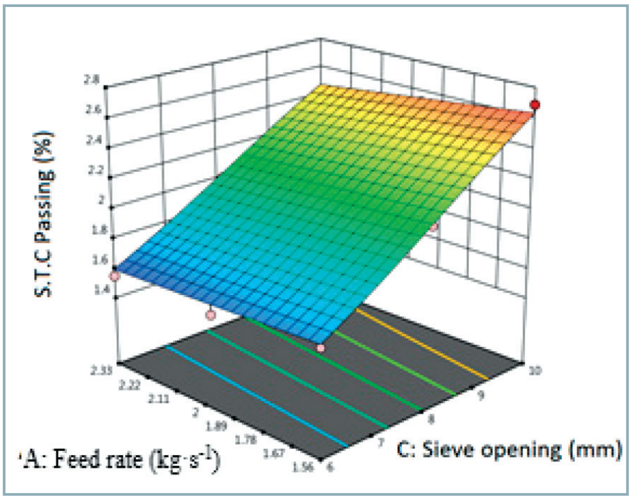

Fig. 3 3D diagram of impacts of material feed rate and sieve opening size on the S.T.C. Passing percentage

MOG content passage (MOG passing)

According to Table 2, all three independent factors significantly affect the MOG Passing through the upper sieve, indicating the importance of the mechanical and pneumatic factors in terms of the MOG Passing and, consequently, the contamination of the clean grain bin. This increases quantitative post-harvest loss. In this section, various mathematical models were used to investigate the effect of the relationship of independent variables on the MOG content passage as well. Finally, the exponential model (Eq. 7) was found to be appropriate (R^2 = 0.94). According to Fig. 4, the MOG Passing content from the upper sieve increases exponentially with a steep slope (similar to linear) following a feed rate increase. These results contradict with the aforementioned. Increased feed rate leads to a decrease in the percentage of materials containing grain passing through (including free grains and s.t.c.) and an increase in MOG passage. Increased feed rate in a farm is affected by increased driving speed and reduced harvest (Mirzazadeh et al., 2011). Based on Fig. 4 and Eq. 7, the MOG Passing content decreases exponentially linearly with increasing fan speed. Increased fan speed leads to an increase in the amount of air blown into the material on the sieve.

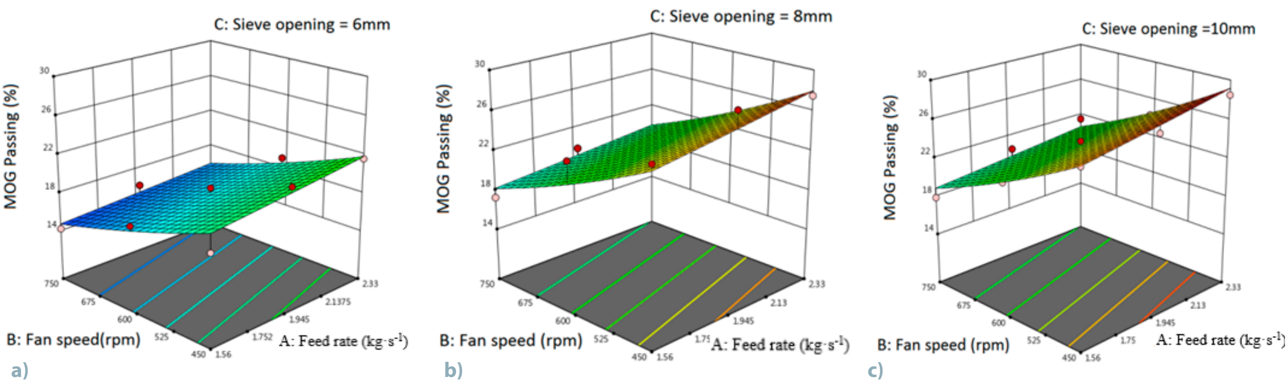

Fig. 4 3D diagram of impacts of material feed rate and sieve opening size on MOG passing content

Table 4 Recommended optimal point for efficient operation of the combine harvester cleaning system

Feed rate ($kg \cdot s^{-1}$)	Fan speed (rpm)	Sieve opening (mm)	Grain passing (%)	S.T.C passing (%)	MOG passing (%)	Desirability
3.33	742	10	65.5	2.3	23.5	0.84

The generated airflow allows more efficient separation of grain from MOG and MOG ejection (mostly straw) from the combine harvester rear due to lower terminal velocity of chaff and small straw pieces than materials containing grain. Finally, the MOG Passing content in the upper sieve increases exponentially with the increasing opening size of the upper sieve. An increased MOG passage through the upper sieve is caused by increased sieve size and increased probability of material passage, as well as decreased air velocity.

Optimization

To obtain optimal conditions for the cleaning section function, desirability functions of dependent variables (Eqs 5–7) were employed, with the results presented in Table 4. According to this table, the maximum Free Grain Passing (65.5%), maximum s.t.c (2.3%), and minimum MOG passage (23.5%) were achieved at a feed rate of 3.33 $kg \cdot s^{-1}$, a fan speed of 741 rpm, and an upper sieve opening size of 10 mm with a desirability value of 0.84, which is considered an acceptable amount.

Conclusion

1. All three independent factors had a significant effect on the grain passage rate from the upper sieve openings. As the upper sieve opening size increased and the feed rate and fan speed decreased, the free grain loss at the upper sieve rear decreased.
2. Mechanical factors had more significant effects on the separation of s.t.c. from other materials and its passage through sieve openings compared to pneumatic factors.
3. All three independent variables had a significant effect on overloading of the upper sieve, contamination of the clean grain bin and increasing quantitative post-harvest loss.
4. The exponential model was found to be appropriate for all three dependent variables.
5. Using the desirability functions of dependent variables, maximum Free Grain Passing (65.5%), maximum s.t.c Passing (2.3%) and minimum MOG passage (23.5%) were obtained with a desirability value of 0.84 at a feed rate of 3.33 $kg \cdot s^{-1}$, a fan speed of 741 rpm and a 10 mm upper sieve opening.

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