Introduction

Harvesting of cereals, incl. wheat has to be carried out within short time in order to prevent losses from shelling grain and possible damage from adverse climatic conditions (Mandradzhiev, 2006; Li et al., 2013; Delchev and Trendafilov, 2013; Petrovna, 2014; Delchev et al., 2016). The technical parameters of grain harvesters that affect the unloading time are the volume of the grain hopper and the flow rate of the unloading screw (Tihanov, 2017). The main feature of the grain hopper emptying systems of harvesters is their design flow rate, which is referred to as the unloading screw flow rate (Trendafilov et al., 2017). In fact, this flow rate is maximally possible and is achieved at nominal angular speed of the engine.

One of the operations in the process of emptying the hopper is its unloading, i.e. the time from switching on the unloading screw until its switching off. The duration of that operation depends on the parameters of the unloading screw, the volume of the grain hopper and the unloading mode of the harvester, i.e. screw shaft rotation frequency (Delchev and Trendafilov, 2015). The advantages of a bigger hopper are that fewer stops for unloading the harvester are made. This leads to reduction of the unproductive time - the idle time for unloading. A bigger hopper has some drawbacks as well. It increases the weight and dimensions of the harvester, resistance to self-propulsion of the machine is greater and consequently fuel consumption. On the other hand, there is a significant soil compaction and problems with the subsequent soil tillage.

The tendency for increasing the volume of grain hoppers is related to the increase in the flow rate of unloading screws. In some grain harvesters this flow rate reaches 140-150 L/s (New Holland, 2017). This makes it possible to significantly reduce the time to empty the hopper. The time from switching on the unloading screw until its switching off (the time for emptying the hopper), regardless of its volume, takes 1.2-2.2 min (Delchev and Trendafolov, 2002). According to the same authors, the duration of emptying the grain hopper also depends on the technical parameters of the grain harvester and is described by the equation (Delchev and Trendafilov, 2015):

\[
T = \frac{V \cdot \rho}{Q} = \frac{V \cdot \rho}{60 \cdot \pi \cdot (d_s^2 - d_l^2) \cdot S \cdot n \cdot \rho} = \frac{4 \cdot V}{60 \cdot \pi \cdot (d_s^2 - d_l^2) \cdot S \cdot n}, \quad h
\]

Where: \( T \) is the time from switching the unloading screw until its switching off, \( h \);
\( Q \) – capacity of the unloading screw, kg/h;
\( V \) – grain hopper volume, \( m^3 \);
\( \rho \) – grain volumetric weight, kg/m\(^3\);
\( d_s \) – screw diameter, m;
\( d_l \) – screw shaft diameter, m;
\( S \) – screw step, m;
\( n \) – rotation frequency, min\(^{-1}\).
According to Trendafilov et al. (2017), the actual unloading time is 142.8% of the theoretical one and an average of 73.1% of the theoretical flow rate of the unloading screw is utilized. These studies were performed under actual production conditions without taking into account the crankshaft speed of the engine during unloading. Another author has investigated the hopper unloading of Claas Lexion 570 harvester in idle position when harvesting wheat under its three hopper emptying modes (Dragoev, 2018). The results obtained show that as the rotation speed of the engine crankshaft decreases, the flow rate of the screw also decreases. High-flow hopper unloading systems require considerable power. For harvesters to be able to harvest and unload the hopper on the move, they are equipped with the so-called dual-power engines. The engine operates at high power only when the unloading screw is switched on.

The objective of this paper is to study the effect of the hopper volume and the flow rate of the unloading screw of grain harvesters on the time from switching on the unloading screw till its switching off.

Material and methods

The survey was conducted in 2019 during wheat harvesting on 15 agricultural farms. A total of 15 grain harvesters were observed, including 14 models from 6 different brands. On all farms the unloading of the hopper was carried out at standstill of the grain harvester. The established harvest organization, the unloading mode and the specific actions of the operators have not been changed.

Table 1. Technical parameters of grain harvesters and results from the study

<table>
<thead>
<tr>
<th>Harvester designation</th>
<th>Number of measurements, N</th>
<th>Hopper volume, V, L</th>
<th>Design flow rate of the unloading screw, q_k, L/s</th>
<th>Average actual time for emptying the hopper, t, s</th>
<th>Actual flow rate of the unloading screw, q, L/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>4</td>
<td>5000</td>
<td>75</td>
<td>114.50</td>
<td>43.67</td>
</tr>
<tr>
<td>K2</td>
<td>6</td>
<td>6200</td>
<td>75</td>
<td>116.84</td>
<td>53.06</td>
</tr>
<tr>
<td>K3</td>
<td>10</td>
<td>8500</td>
<td>105</td>
<td>111.12</td>
<td>76.49</td>
</tr>
<tr>
<td>K4</td>
<td>6</td>
<td>8500</td>
<td>85</td>
<td>119.00</td>
<td>71.43</td>
</tr>
<tr>
<td>K5</td>
<td>6</td>
<td>8500</td>
<td>105</td>
<td>116.17</td>
<td>73.17</td>
</tr>
<tr>
<td>K6</td>
<td>8</td>
<td>8600</td>
<td>100</td>
<td>118.87</td>
<td>72.34</td>
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<tr>
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<td>8600</td>
<td>70</td>
<td>148.11</td>
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<td>54.79</td>
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<td>186.66</td>
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<td>110</td>
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<td>50.32</td>
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<tr>
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<td>10000</td>
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<td>130.29</td>
<td>76.75</td>
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</tr>
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<td>6</td>
<td>14100</td>
<td>135</td>
<td>128.43</td>
<td>109.78</td>
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<tr>
<td>K15</td>
<td>7</td>
<td>14100</td>
<td>135</td>
<td>121.94</td>
<td>115.63</td>
</tr>
<tr>
<td>Average:</td>
<td></td>
<td></td>
<td></td>
<td>134.85</td>
<td>69.63</td>
</tr>
</tbody>
</table>

The actual time for unloading the grain hopper is determined by measuring the period from switching on the unloading screw until its switching off. The measured average value for the respective grain harvester is used to determine the actual flow rate of the unloading screw by the following equation:

$$ q = \frac{V}{t}, \frac{L}{s} $$  \hspace{1cm} (2)

Where: $q$ is the actual flow rate, L/s; $V$ – the grain hopper volume, L; $t$ – mean value of the actual time for unloading the grain hopper, s.

Table 1 presents the technical parameters of the studied harvesters and the models and brands are replaced by conventional symbols. Some of the harvesters are the same, therefore the table contains the same characteristics. The table shows that the study involved grain harvesters with hopper volume from 5000 to 14100 L, the majority being with a volume of 8000-9000 L. The average actual unloading time of the hoppers is 134.85 s, varying between 111.12 to 186.66 s among the individual harvesters.

Results and discussion

Figure 1 shows graphically the design and actual flow of the unloading screw in the various harvesters. It is evident that for all grain harvesters the actual unloading flow rate is less than the design flow rate. Figure 1 also shows the relationship between the unloading flow rate of the screw and the volume of the grain hopper of the harvesters included in the study. It is also evident that the relationship between the two parameters is linear, i.e. with the increase in the grain hopper volume manufacturers...
design greater flow rate of the unloading system to keep the total unloading time below 2 min. The coefficient of certainty using the design flow rate is $R^2 = 0.7394$, and when using the actual flow rate it is $R^2 = 0.7747$, i.e. an average of 75.71% of the change in design and actual flow rate is due to the grain hopper volume.

![Figure 1](image)

**Figure 1.** Impact of the design and actual flow rate of the unloading screw and the hopper volume for different grain harvesters

Table 2 presents the results from a multivariate regression analysis of the effect of the hopper volume ($V$) and the actual flow rate of the unloading screw ($q$) on the time from switching on the unloading screw until its switching off ($t$) for different grain harvesters.

From Table 2 it is evident that the effect of the hopper volume and the actual flow rate of the unloading screw on the time from switching on the unloading screw till its switching off ($t$) for different grain harvesters.

![Table 2](image)

**Table 2.** Results from the multivariate regression analysis on the effect of the grain hopper volume and the actual flow rate of the unloading screw on the time from switching on the unloading screw until its switching off

A graphical representation of the regression model for $t$ (time from switching on the unloading screw until its switching off) was made by taking into account the effect of the times $V$ (the volume of the harvester grain hopper) and $q$ (the actual flow rate of the unloading screw of harvesters) as significant. Figure 2 shows graphically the response surface for $t = f(V, q)$. The grain hopper volume ($V$) and the actual flow rate of the unloading screw ($q$) significantly affect the time from switching on the unloading screw until its switching off ($t$). This is due to the fact that the maximum flow rates of the unloading screws are not used. Unloading is usually done at lower engine speeds, reciprocally of the unloading screw (the unloading system). Also, the valves in the hoppers regulating the flow of grain to the unloading system are not regulated for the respective crop.

![Figure 2](image)

**Figure 2.** Changing the time from switching on the unloading screw till its switching off ($t$) depending on the grain hopper volume ($V$) and the actual flow rate of the unloading screw ($q$) in grain harvesters

![Figure 3](image)

**Figure 3.** Lines of uniform response to the time from switching on the unloading screw until its switching off ($t$) depending on the grain hopper volume ($V$) and the actual flow rate of the unloading screw ($q$) in grain harvesters
Figure 3 shows graphically the lines of the same response $t= f (V, q)$ for the mathematical model obtained from the time of switching on the unloading screw till its switching off ($t$). The figure shows the area of change of factors in which the parameter has the highest values. This happens when both factors are at their upper levels. The results obtained for both technical parameters – grain hopper volume and actual flow rate of the unloading screw in grain harvesters can be used for optimizing transport service as well as for minimizing costs in the technological process at harvesting.

**Conclusion**

It was found that: a) that the actual time for emptying the hoppers of the studied harvesters was 134.85s on average and ranged from 111.12-186.66 s (2-3 min), with actual flow rate of the unloading screw 69.63 L/s on average; b) the time for emptying the hopper is mainly influenced by the grain hopper volume and the actual flow rate of the unloading screw of grain harvesters; c) a multivariate regression analysis of the effect of the hopper volume and the actual actual flow rate of the unloading screw on the time from switching on the unloading screw till its switching off in various harvesters was carried out; the coefficient of certainty $R^2= 0.828$ shows that 83% of the change in the hopper emptying time is due to the change in the material times and 17% on the influence of the unmanageable factors; d) an adequate mathematical model of the effect of the hopper volume and the flow rate of the unloading screw of grain harvesters on the time of emptying the grain hopper in real production conditions is created; e) the results also can be used for minimizing costs in the technological process at harvesting.

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