Aerodynamic properties of Turgenia latifolia seeds and wheat kernels

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Abstract. Aerodynamic properties of solid materials have long been used to convey and separate seeds and grains during post harvest operations. Turgenia latifolia (broadleaf false carrot) seeds that interfere with milling of wheat can be separated by some type of pneumatic means if aerodynamic properties of these two materials are well known. The objective of this study was evaluation of the aerodynamic properties of Turgenia latifolia seeds and wheat kernels as a function of moisture content, 7 to 20.8% w.b. The results showed that the terminal velocity of wheat kernels increased nonlinearly from 9.587 to 9.25 m s\(^{-1}\) for an increase in moisture content. Over this same moisture content the terminal velocity of Turgenia latifolia seeds varied from 6.775 to 6.877 m s\(^{-1}\). The drag coefficient of wheat kernels and Turgenia latifolia seeds decreased nonlinearly from 0.0543 to 0.0528 and 0.0512 to 0.0458, respectively, as moisture content increased from 7 to 20.8% w.b. The analysis of variance showed that there was a significant difference between the terminal velocity of wheat kernels and the drag coefficient of wheat and Turgenia latifolia seeds at the 1% probability level. The moisture content had a significant effect on the terminal velocity of wheat kernels.

Keywords: aerodynamic properties, separation, Turgenia latifolia, wheat

INTRODUCTION

In handling and processing of agricultural products air or water are often used as a carrier transport for the separation of the desirable product from that of unwanted materials (Mohsenin, 1978). Seed separation can be accomplished by using pneumatic separators, screen cleaners, or gravity tables. Many commercial cleaners incorporate more than one of these cleaning methods (Hauhouot et al., 2000). The pneumatic separation and conveying systems have been in use in agricultural machinery and food processing equipment for many years. When an air stream is used for separating a product such as wheat from its associated foreign materials, such as straw and chaff, knowledge of aerodynamic characteristics of all the particles involved is necessary. This helps to define the range of air velocities for effective separation of the grain from foreign materials. For this reason, the terminal velocity \(V_T\) has been used as an important aerodynamic characteristic of materials in such applications as pneumatic conveying and their separation from foreign materials (Mohsenin, 1978).

Turgenia latifolia from the Apaceae family is a summer annual weed. This weed is common in wheat fields of Iran and the Middle East region. Its seeds have an adverse effect on the quality of the flour if they are not separated before or during the milling process. Separation of Turgenia latifolia seeds from wheat kernels in the milling process is very difficult due to their morphological feathers. To overcome this problem, some type of equipment is needed to be designed which performs this separation. However, in order to do this, thorough knowledge on the aerodynamic properties of wheat as well as Turgenia latifolia seeds may lead to a point that some type of pneumatic device can be envisaged.

Several investigators determined the \(V_T\) of various seeds such as African breadfruit seeds by Omobuwajo et al. (1999), amaranth seeds by Kram and Szot (1999), cheat seed by Hauhouot et al. (2000), millet grain by Baryeh (2002), pine nuts by Ozguven and Vursavus (2005), wheat kernel by Kho-shaghaza and Mehdizadeh (2006), makhana by Jha and Kachru (2007) and pistachio nut by Razavi et al. (2007). But there is no information about the aerodynamic properties of Turgenia latifolia seed.

The objective of this study was to investigate the aerodynamic properties of Turgenia latifolia seeds and wheat (cv. Sardary) kernels as a function of moisture content. Tests were conducted over a range of moisture contents from 7 to 20.8% w.b., which spans the moisture range of harvest to the milling operation.

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MATERIALS AND METHODS

Wheat and *Turgenia latifolia* seeds were cleaned manually to remove foreign materials such as dust, dirt, stones, chaff and broken kernels. The seeds were then classified into two grades based on their length, cut points being 6.92 and 7.54 mm for wheat and *Turgenia latifolia* seeds, respectively. Grade A and B referred to above and below the cut points, respectively.

The initial moisture content of both types of seeds was determined using oven tests at 103±1°C for 19 h (ASAE, 1998). The initial moisture content of wheat and *Turgenia latifolia* seeds was 10 and 7% w.b., respectively. The seeds were conditioned to higher moisture content by adding pre-defined amounts of distilled water. The samples were then stored at 5°C for a week to enable the moisture to distribute uniformly throughout the seeds (Al-Mahasneh and Rababa, 2007).

Wheat and *Turgenia latifolia* seeds were left to dry in the oven at 70 and 30°C, respectively, for different periods of times, to obtain five levels of moisture content, namely, 20.8, 17, 14, 10 and 7% w.b.

EXPERIMENTAL APPARATUS

To determine the *V*<sub>t</sub> value of wheat and *Turgenia latifolia* seeds, a vertical wind tunnel was designed based on recommendations by Tabak and Wolf (1998) and Afonso et al. (2007). A centrifugal fan powered by one HP motor was used in the inlet of the wind tunnel to supply air flow. The air flow rate of the fan was controlled at inlet by a diaphragm. To measure the *V*<sub>t</sub> of the seeds, a uniform velocity field was required in the cross section of the tunnel, where seeds were suspended. For this purpose, two straightener sections were set up which consisted of one layer of fine wire mesh screen located above the honeycomb. The final section of the wind tunnel consisted of a plexiglass region where the *V*<sub>t</sub> of grain was measured.

To determine the terminal velocity, each seed was placed in the centre of the cross section of the wind tunnel on the screen. The air flow was then increased until the seed flotation point. At this moment, when the rotational movement of the seed was lowest, the air velocity was measured using a hot-wire anemometer with an accuracy of 0.1 m s<sup>-1</sup>. The *V*<sub>t</sub> of each seed was measured two times. For each condition the *V*<sub>t</sub> was calculated as the average of the velocity values obtained at the centre of the test section and at the four equidistantly distributed points on two orthogonal axes located at the test section. To determine the *V*<sub>t</sub> at each moisture content level, five seeds were selected and used as five replications in the statistical analysis.

In free fall, the object will attain a constant velocity, *V*<sub>t</sub>, at which the gravitational force, *F*<sub>g</sub>, equals the resisting upward drag force, *F*<sub>r</sub> (Mohsenin, 1978). This constant velocity is called *V*<sub>t</sub>:

If *F*<sub>g</sub> = *F*<sub>r</sub> ⇒ *V* = *V*<sub>t</sub>

By substituting the expressions of *F*<sub>g</sub> and *F*<sub>r</sub> in the above equation, the expression for the *V*<sub>t</sub> will be:

\[
\left(\frac{\rho_t - \rho_f}{\rho_t}\right) = \frac{1}{2} CA_p \rho_f V_t^2,
\]

\[
V_t = \left[\frac{2w(\rho_t - \rho_f)}{CA_p} \rho_t \rho_f\right]^{1/2},
\]

\[
C_d = \frac{2w(\rho_t - \rho_f)}{V_t^2 A_p \rho_t \rho_f},
\]

\[
A_p = \frac{\pi}{4} LW,
\]

where: *A*<sub>p</sub> is projected area (m<sup>2</sup>), *C*<sub>d</sub> is drag coefficient (dimensionless), *L* is length of kernel (mm), *V*<sub>t</sub> is terminal velocity (m s<sup>-1</sup>), *w* is weight of kernel (kg m<sup>-2</sup>), *W* is width of kernel (mm), *ρ*<sub>p</sub>, *ρ*<sub>f</sub> are seed and air densities (kg m<sup>-3</sup>).

The drag coefficient was calculated using Eq. (1). To calculate the drag coefficients of two products (at both grades), the *V*<sub>t</sub> values were measured using the procedure described in the previous section. The true density of the seeds was measured using toluene displacement method (Chakraverty and Poul, 2001; Mohsenin, 1978). The projected area of the seeds was estimated using Eq. (2). The major dimensions of the seeds (*L* and *W*) were also measured using a digital vernier caliper with an accuracy of ±0.01 mm (Gupta et al., 2007). The value of air density was taken as 1.1774 kg m<sup>-3</sup> at temperature of 27°C (Irwan and Ugbeke, 2003). Each experiment was conducted at all moisture content levels.

Data analysis of the *V*<sub>t</sub> and the drag coefficient of wheat and *Turgenia latifolia* seeds were carried out using a nested split plot form arranged in Complete Randomised Design (CRD) with five replications. Wheat and *Turgenia latifolia* seeds at two size classifications (A and B) were used as a main plot and five moisture content levels (7, 10, 14, 17 and 20.8% w.b.) were used as a sub plot. Mean comparison of factors was carried out at 5% probability level. The *V*<sub>t</sub> and the moisture content data of different seeds were fitted to linear, power, exponential and polynomial models. The models were evaluated according to the statistical criterion *R*<sup>2</sup> for verifying the adequacy of fit. The best model with the highest *R*<sup>2</sup> was selected to predict the *V*<sub>t</sub> of seeds as a function of the moisture content. Data were analysed by MSTATC, SPSS and MATLAB software.
RESULTS AND DISCUSSION

The results determined that there was a significant difference between the $V_t$ of wheat and *Turgenia latifolia* seeds (at both grades A and B). Also the effect of seed moisture content on this property was significant (Table 1). The $V_t$ of wheat kernels at both grades A and B increased from 9.25 to 9.587 m s$^{-1}$ and from 8.353 to 8.757 m s$^{-1}$, respectively, as the moisture content increased from 7 to 20.8% w.b. (Fig. 1).

The maximum $V_t$ value of wheat kernels was obtained in grade A (9.58 m s$^{-1}$), at a moisture content of 20.8% w.b., and the minimum amount was obtained in grade B (8.35 m s$^{-1}$), at a moisture content of 7% w.b. However, in a comparison of the means, the moisture content did not significantly affect the $V_t$ of *Turgenia latifolia* seeds at both grades; although as moisture content increased from 7 to 20.8% w.b., the $V_t$ of *Turgenia latifolia* seeds varied from 6.775 to 6.887 m s$^{-1}$ and from 5.853 to 5.983 m s$^{-1}$ at both grades A and B, respectively. *Turgenia latifolia* seeds had the maximum value of $V_t$ in grade A (6.88 m s$^{-1}$), at the moisture content of 20.8% w.b., and minimum value of $V_t$ of *Turgenia latifolia* seeds was related to grade B (5.85 m s$^{-1}$), at the moisture content of 7% w.b. These results are in agreement with published literature for some seeds. Gupta et al. (2007) showed that in the moisture range of 6 to 14% d.b., the $V_t$ of NSFH-36, PSF-118 and Hybrid SH-3322 variety of sunflower seed increased from 2.93 to 3.28, 2.54 to 3.04, and 2.98 to 3.53 m s$^{-1}$, respectively. Zewdu (2007) measured the $V_t$ of Tef grains. He reported that it increased linearly from 3.08 to 3.96 m s$^{-1}$ with increasing moisture content from 6.5 to 30.1% w.b. Hauhouot et al. (2000) showed that the $V_t$ of wheat is 7.84 m s$^{-1}$. The $V_t$ of millet grain varied from 2.75 to 4.63 m s$^{-1}$ for an increase in moisture content from 5 to 22.5% d.b. (Baryeh, 2002). Similar results were reported for cotton seeds (Tabak and Wolf, 1998), coffee cherries and beans (Afonso et al., 2007), African yam bean (Irtwange and Ugbeke, 2003).

The $V_t$ data for wheat kernels were fitted as a function of moisture content to four mathematical models. These models were evaluated for verifying the adequacy of fit using the $R^2$ value. By comparing the average values of $R^2$, it was obvious that the polynomial model had the highest $R^2$ value (Table 2). Accordingly, the polynomial model was selected as a suitable model to predict the $V_t$ of wheat kernels as a function of moisture content. Razavi et al. (2007) developed a linear equation between the $V_t$ of pistachio nut and kernel as a function of moisture content. Zewda (2007) reported that the $V_t$ of Tef grain was linearly related to moisture content. However, Afonso et al. (2007) reported a nonlinear equation for the $V_t$ of coffee cherry and bean as a function of combination of moisture content and true density.

As shown in Fig. 1, the $V_t$ values of wheat kernels for both grades A and B were higher than those of *Turgenia latifolia* seeds at both grades and at all moisture content levels. The $V_t$ values of wheat and *Turgenia latifolia* seeds could be arranged in decay order from maximum to minimum as: wheat grade A, and B, *Turgenia latifolia* grade A and B. At least, there was 1.5 m s$^{-1}$ difference between the $V_t$ of wheat grade B and Turgenia latifolia grade A seeds.

In the milling process the operation of secondary separation of foreign materials from wheat kernels was conducted at a moisture content of 13-14% w.b. At these moisture content levels, the difference between the $V_t$ of wheat and *Turgenia latifolia* seeds was about 2 m s$^{-1}$. Therefore, this difference was large enough to successfully separate *Turgenia latifolia* seeds from wheat kernels using equipment which operates on the basis of the aerodynamic properties such as the $V_t$.

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**Table 1.** Summary of ANOVA for the $V_t$ and the drag coefficient

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Mean squares</th>
<th>Drag coefficient (x10$^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed</td>
<td>3</td>
<td>62.294*</td>
<td>3.186.840*</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>0.259</td>
<td>86.797</td>
</tr>
<tr>
<td>Moisture content</td>
<td>16</td>
<td>0.063*</td>
<td>10.853 n.s.</td>
</tr>
<tr>
<td>Error</td>
<td>64</td>
<td>0.021</td>
<td>14.535</td>
</tr>
</tbody>
</table>

*Significant difference at 1% probability level, n.s. – no significant.

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**Table 2.** Polynomial equations for predicting $V_t$ of wheat kernels as a function of the moisture content

<table>
<thead>
<tr>
<th>Grade</th>
<th>Regression equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$V_t = 0.0003 Mc^2 + 0.017 Mc + 9.130$</td>
<td>0.957</td>
</tr>
<tr>
<td>B</td>
<td>$V_t = 0.0010 Mc^2 + 0.007 Mc + 8.255$</td>
<td>0.994</td>
</tr>
</tbody>
</table>
The values of the drag coefficient and the projected area of wheat and *Turgenia latifolia* seeds were calculated using Eqs (1) and (2) by measuring the $V_t$, true density and the two principal dimensions (length and width) of seeds (Table 3). The analysis of variance showed that there was a significant difference between the drag coefficients of wheat and *Turgenia latifolia* seeds (at both grades). The drag coefficients values of wheat kernels in grade A and B decreased from 0.0543 to 0.0528 and from 0.0570 to 0.0560 as moisture content increased from 7 to 20.08% w.b. In grade A and B, the drag coefficients of *Turgenia latifolia* seeds decreased from 0.0512 to 0.0458 and 0.0338 to 0.0295, respectively, over this same moisture content (Fig. 2). The drag coefficients of wheat kernels were higher than those of *Turgenia latifolia* seeds at both grades. This may be due to the differences in surface properties, true densities, shapes and sizes.

**Table 3.** Average values of $V_t$, true density, dimensions, projected area and drag coefficient of seeds at different moisture contents

<table>
<thead>
<tr>
<th>Moisture content (% w.b.)</th>
<th>Terminal velocity ($m/s$) Mean</th>
<th>SD*</th>
<th>True density ($kg/m^3$) Mean</th>
<th>SD</th>
<th>Length (mm) Mean</th>
<th>SD</th>
<th>Width (mm) Mean</th>
<th>SD</th>
<th>Projected area ($mm^2$) Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat A</td>
<td>20.8</td>
<td>9.58</td>
<td>0.32</td>
<td>1309.363</td>
<td>1.00</td>
<td>8.144</td>
<td>0.37</td>
<td>3.600</td>
<td>0.27</td>
<td>23.021</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>9.51</td>
<td>0.24</td>
<td>1275.900</td>
<td>8.33</td>
<td>8.006</td>
<td>0.36</td>
<td>3.530</td>
<td>0.25</td>
<td>22.221</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>9.37</td>
<td>0.32</td>
<td>1271.993</td>
<td>11.56</td>
<td>7.916</td>
<td>0.37</td>
<td>3.510</td>
<td>0.29</td>
<td>21.839</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9.35</td>
<td>0.31</td>
<td>1279.086</td>
<td>3.55</td>
<td>7.865</td>
<td>0.35</td>
<td>3.480</td>
<td>0.28</td>
<td>21.494</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>9.25</td>
<td>0.26</td>
<td>1274.550</td>
<td>13.50</td>
<td>7.814</td>
<td>0.33</td>
<td>3.440</td>
<td>0.26</td>
<td>21.151</td>
</tr>
<tr>
<td>Wheat B</td>
<td>20.8</td>
<td>8.75</td>
<td>0.20</td>
<td>1303.023</td>
<td>19.51</td>
<td>6.558</td>
<td>0.67</td>
<td>2.882</td>
<td>0.33</td>
<td>14.831</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>8.61</td>
<td>0.19</td>
<td>1315.778</td>
<td>11.12</td>
<td>6.482</td>
<td>0.69</td>
<td>2.792</td>
<td>0.22</td>
<td>14.218</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>8.52</td>
<td>0.21</td>
<td>1314.100</td>
<td>15.39</td>
<td>6.444</td>
<td>0.71</td>
<td>2.782</td>
<td>0.20</td>
<td>14.072</td>
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<tr>
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<td>10</td>
<td>8.38</td>
<td>0.16</td>
<td>1284.728</td>
<td>4.69</td>
<td>6.434</td>
<td>0.70</td>
<td>2.766</td>
<td>0.19</td>
<td>13.978</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>8.35</td>
<td>0.11</td>
<td>1283.515</td>
<td>12.19</td>
<td>6.398</td>
<td>0.68</td>
<td>2.730</td>
<td>0.19</td>
<td>13.718</td>
</tr>
<tr>
<td><em>Turgenia latifolia</em> A</td>
<td>20.8</td>
<td>6.88</td>
<td>0.20</td>
<td>996.023</td>
<td>18.02</td>
<td>10.334</td>
<td>0.67</td>
<td>3.832</td>
<td>0.33</td>
<td>31.140</td>
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<tr>
<td></td>
<td>17</td>
<td>6.85</td>
<td>0.19</td>
<td>993.441</td>
<td>2.34</td>
<td>10.313</td>
<td>0.69</td>
<td>3.773</td>
<td>0.22</td>
<td>30.008</td>
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<tr>
<td></td>
<td>14</td>
<td>6.82</td>
<td>0.21</td>
<td>994.810</td>
<td>10.41</td>
<td>10.292</td>
<td>0.71</td>
<td>3.714</td>
<td>0.20</td>
<td>30.008</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>6.8</td>
<td>0.16</td>
<td>976.455</td>
<td>12.49</td>
<td>10.265</td>
<td>0.70</td>
<td>3.660</td>
<td>0.19</td>
<td>29.520</td>
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<tr>
<td></td>
<td>7</td>
<td>6.77</td>
<td>0.11</td>
<td>958.026</td>
<td>3.08</td>
<td>10.238</td>
<td>0.68</td>
<td>3.560</td>
<td>0.19</td>
<td>28.654</td>
</tr>
<tr>
<td><em>Turgenia latifolia</em> B</td>
<td>20.8</td>
<td>5.98</td>
<td>0.13</td>
<td>1057.642</td>
<td>22.68</td>
<td>7.374</td>
<td>0.86</td>
<td>2.826</td>
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<td>7.310</td>
<td>0.88</td>
<td>2.753</td>
<td>0.15</td>
<td>15.797</td>
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<td>5.96</td>
<td>0.24</td>
<td>1053.279</td>
<td>15.24</td>
<td>7.268</td>
<td>0.90</td>
<td>2.720</td>
<td>0.14</td>
<td>15.510</td>
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<td></td>
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<td>5.92</td>
<td>0.18</td>
<td>1044.874</td>
<td>9.64</td>
<td>7.211</td>
<td>0.92</td>
<td>2.677</td>
<td>0.13</td>
<td>15.130</td>
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<tr>
<td></td>
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<td>5.85</td>
<td>0.17</td>
<td>1016.881</td>
<td>26.75</td>
<td>7.168</td>
<td>0.93</td>
<td>2.645</td>
<td>0.12</td>
<td>14.847</td>
</tr>
</tbody>
</table>

*Standard deviation.
of the materials. But the drag coefficients were not affected significantly by moisture content of wheat and Turgenia latifolia seeds (Table 1). This was due to the fact that the parameters associated with Eq. (1) increased along with each other as moisture content increased. Therefore, the drag coefficient of seeds did not significantly change over this range of moisture contents. These results are in agreement with some published literature. Afonso et al. (2007) reported that the drag coefficient of coffee cherries (cv. Catual) decreased from 0.05 to 0.03 as moisture content increased from 10.7 to 53.9% w.b. Gupta (2007), Irtwange and Ugbeka (2003) reported similar results for sunflower seed and African yam bean (cv. TSS 138), respectively. However, some odd results have been reported for some products. Irtwange and Ugbeka (2003) reported similar results for sunflower seed and African yam bean (cv. TSS 138), respectively. However, some odd results have been reported for some products. Irtwange and Ugbeka (2003) reported that the maximum difference of pistachio nut and its kernel as affected by moisture content on some physical properties of green wheat. J. Food Eng., 79, 1407-1473.


CONCLUSIONS

1. The \( V_t \) value of wheat kernels was higher than those of Turgenia latifolia seeds and the difference between the maximum \( V_t \) of Turgenia latifolia seeds and minimum \( V_t \) of wheat kernels was about 1.5 m s\(^{-1}\). Therefore, Turgenia latifolia seeds can be separated from wheat kernels successfully if the air velocity value is adjusted according to the \( V_t \) of Turgenia latifolia seeds.

2. In a milling plant separation can be performed either as a primary or secondary operation after the moisture content of the kernels has been increased through humidification. The \( V_t \) values of wheat increased for an increase in moisture content while the \( V_t \) values of the Turgenia latifolia seeds remained approximately the same for an increase in moisture content. Therefore, the maximum difference between the \( V_t \) values of wheat and Turgenia latifolia would be found in the secondary separation process. Consequently, a more efficient separation process of Turgenia latifolia from wheat would be done in the secondary operation in practice.

3. There were significant differences between the drag coefficients of wheat and Turgenia latifolia seeds at both grades, however, the drag coefficients of both wheat and Turgenia latifolia seeds were not affected by moisture content.

Generally, to predict the \( V_t \) values of seeds by calculation method and related equations at any moisture content levels, it is advisable to use unique average values of drag coefficients of seeds at the studied moisture content levels.

REFERENCES


