The effects of heating temperatures and time on deformation energy and oil yield of sunflower bulk seeds in compression loading

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Abstract. The deformation energy (J) and percentage oil yield (%) of sunflower bulk seeds under the influence of heat treatment temperatures and heating time were examined in compression test using the universal compression testing machine and vessel diameter of 60 mm with a plunger. The heat treatment temperatures were between 40 and 100 °C and the heating time at specific temperatures of 40 and 100 °C ranged from 15 to 75 minutes. The bulk sunflower seeds were measured at a pressing height of 60 mm and pressed at a maximum force of 100 kN and speed of 5 mm/min. Based on the compression results, the deformation energy and oil yield increased along with increasing heat treatment temperatures. The results were statistically significant (p < 0.05). At a 40 °C heat treatment temperature in relation to varying heating time, deformation energy increased while the percentage oil yield decreased. However, at a 100 °C, the deformation energy almost showed no correlation but the oil yield similarly decreased. From the ANOVA statistical analysis, the effect of heating time at 40 and 100 °C heat treatment temperatures on deformation energy and oil yield was not significant (p > 0.05).

1. Introduction
The use of vegetable oils as part of renewable energy sources is rapidly growing over the concerns of fossil fuels or climate change [1]. Although renewable energy can provide a clean source of electricity, petroleum fuels still account for the vast majority of the world’s energy generation [2]. Sunflower (Helianthus annus L.) produces edible vegetable oil with an annual production of 25.1 million tonnes being one of the potential feedstocks for biodiesel production [3]. The conventional method for sunflower oil extraction involves seed preparation, mechanical extraction and solvent extraction using n-hexane [4, 5]. Mechanical pressing is the most common method for oil extraction from oilseeds especially in the rural areas of developing countries [6]. The main purpose of oilseed post-harvest technology is the recovery of percentage oil yield and quality of oil which is dependent on several factors such as storage, pretreatment and processing [7, 8]. Studies have shown that applied pressure, pressing or heating temperature, heating time, pressing time, pressing speed and seed moisture content thus influence the oil recovery and energy requirement [9, 10, 11, 12]. To obtain a higher percentage oil yield and minimum residual oil in the seed cake, it is very important to control the above-mentioned processing parameters during oil extraction process [13]. The study was aimed to investigate the influence of heat treatment temperatures and heating time on deformation energy and percentage oil yield of sunflower bulk seeds in compression loading and also to describe analytically the dependency between the force and deformation curves as well as the deformation energy.
2. Materials and methods

2.1 Sample and compression test

A sunflower bulk seed of moisture content of 12 w.b. % was used for the compression test. The moisture content was determined using the procedure specified by [14]. The equipment (MEMMERT GmbH + Co. KG, Germany) was used for the samples heat treatment temperatures from 40 to 100 °C and heating time from 15 to 75 minutes at specific heat treatment temperatures of 40 and 100 °C respectively. A universal testing machine of type ZDM 50, Czech Republic together with a pressing vessel of diameter 60 mm with a plunger were used for recording the data points of force (N) and deformation (mm) of sunflower bulk seed of 60 mm measured pressing height [15]. A maximum force of 100 kN and speed of 5 mm/min were applied. The test was repeated twice. The determined amounts namely the deformation energy (J) and oil yield (%) were statistically evaluated using the Statistica software (version 13) [16]. The deformation energy and oil yield were numerically determined based on the equations proposed by the authors [17, 18]. The theoretical relationships between the force and deformation curves as well as the deformation energy were described by the tangent curve mathematical model [19, 20] applicable in Mathcad software (version 14) [21].

3. Results and discussion

The measured amounts of deformation, oil yield and deformation energy in relation to heat treatment temperatures and heating time are presented in Tables 1 to 3 respectively.

Table 1. Measured data (mean±standard deviation) of sunflower bulk seeds at varying temperatures

| Temperatures (°C) | Deformation (mm) | Oil yield (%) | Deformation energy (J) |
|-------------------|------------------|--------------|------------------------|
|                   | *Numerical       | **Analytical |                       |
| **Control**       | 43.400±0.962     | 19.062±0.431 | 466.481±3.007          | 434.481±3.278 |
| 40                | 42.955±0.741     | 18.092±0.701 | 465.250±9.159          | 546.102±0.903 |
| 50                | 44.255±0.813     | 18.199±0.103 | 470.057±7.678          | 526.211±13.062 |
| 60                | 43.425±0.898     | 19.068±0.087 | 470.539±13.067         | 453.991±18.435 |
| 70                | 42.000±0.594     | 18.431±0.881 | 489.051±8.034          | 461.813±5.963 |
| 80                | 42.805±0.559     | 18.028±0.299 | 500.084±4.958          | 514.531±50.973 |
| 90                | 43.905±1.054     | 20.727±0.053 | 508.325±7.788          | 588.006±29.070 |
| 100               | 43.375±0.106     | 19.120±0.163 | 510.661±3.155          | 608.121±13.063 |

* Based on the area of a trapezoid [17], ** Based on the tangent curve model [19, 20]

Table 2. Measured data (mean±standard deviation) of sunflower bulk seeds at 40 °C

| Heating time (min) | Deformation (mm) | Oil yield (%) | Deformation energy (J) |
|--------------------|------------------|--------------|------------------------|
|                    | *Numerical       | **Analytical |                       |
| **Control**        | 42.955±0.741     | 18.092±0.701 | 465.288±9.059          | 478.305±9.673 |
| 15                 | 45.375±0.375     | 18.979±0.749 | 489.252±17.171         | 500.232±2.137 |
| 30                 | 44.975±0.686     | 18.176±0.103 | 495.644±9.134          | 477.881±25.710 |
| 45                 | 43.990±1.655     | 16.697±1.641 | 506.362±6.164          | 533.771±1.740 |
| 60                 | 43.365±3.429     | 16.831±0.959 | 509.229±12.489         | 554.103±24.579 |
| 75                 | 43.920±0.467     | 18.024±0.462 | 509.229±12.489         | 554.103±24.579 |

Based on the ANOVA statistical analysis, the heat treatment temperatures significantly (p < 0.05) influenced the amounts of the deformation energy and percentage oil yield (Table 1). This means that the measured amounts mentioned above increased along with increasing heat treatment temperatures with a very high correlation of 0.935 and 0.941 respectively. The influence of heating time at particular heat treatment temperatures of 40 and 100 °C on deformation energy and oil
yield was not statistically significant \( (p > 0.05) \) in terms of decreasing or increasing trends. However, from the experimental data, the deformation energy increased in relation to the heating time at 40 °C but slightly decreased at 100 °C. The oil yield, on the other hand, decreased at both heat treatment temperatures.

Table 3. Measured data (mean±standard deviation) of sunflower bulk seeds at 100 °C

| Heating time (min) | Deformation (mm) | Oil yield (%) | Deformation energy (J) |
|-------------------|------------------|---------------|------------------------|
|                   | *Control         |               | **Analytical           |
| 43.375±0.106      | 19.120±0.163     | 510.661±3.155 | 608.121±13.063         |
| 41.540±0.651      | 20.805±0.455     | 508.488±11.635| 550.307±81.070         |
| 43.205±0.629      | 20.143±1.248     | 517.113±1.874 | 529.770±9.656          |
| 43.025±0.035      | 20.141±0.345     | 509.943±0.103 | 562.462±12.590         |
| 42.770±0.509      | 19.268±0.926     | 506.657±0.389 | 553.101±45.837         |
| 41.910±0.778      | 19.124±0.108     | 509.362±0.844 | 532.237±9.099          |

Table 4. One-way ANOVA analysis of measured data at varying heat treatment temperatures

| Measured data | \( F_{\text{ratio}} \) | \( F_{\text{critical}} \) | \( p \) | \( R^2 \) |
|---------------|-------------------------|--------------------------|--------|----------|
| Deformation energy (J) | 8.193      | 3.866        | 0.006  | 0.875    |
| Oil yield (%)     | 9.115       | 3.866        | 0.005  | 0.887    |

\( p < 0.05 \) level of significance or \( F_{\text{ratio}} > F_{\text{critical}} \) is significant

Table 5. Factorial or Repeated measures ANOVA analysis of measured data at both 40 and 100 °C in relation to heating time

| Measured data | \( F_{\text{ratio}} \) | \( F_{\text{critical}} \) | \( p \) | \( R^2 \) |
|---------------|-------------------------|--------------------------|--------|----------|
| Deformation energy (J) | 2.584 | 3.478 | 0.078 | 0.699 |
| Oil yield (%)     | 5.344       | 3.478        | 0.008  | 0.828    |

\( p > 0.05 \) level of significance or \( F_{\text{ratio}} < F_{\text{critical}} \) is non–significant

The theoretical description of the experimental dependency between the force and deformation curves of a sunflower bulk seed in relation to heat treatment temperatures is shown in Figure 1 similar to varying heating time at specific temperatures of 40 and 100 °C respectively. The area under the curve is the numerical deformation energy [17] (Tables 1 to 3) which can also be determined analytically using the tangent curve model [19, 20]. The determined coefficients of the tangent curve model using Mathcad 14 software are presented in Tables 6 to 8 respectively. The coefficients were statistically significant with high coefficients of determination \( (R^2) \) where the \( F_{\text{ratio}} \) values were higher than the values of the \( F_{\text{critical}} \). In addition, the \( p \) values were higher than the significance level of 0.05. The tangent curve mathematical model considers the boundary conditions of the compression process being zero compressive force relate to zero deformation, deformation thus reaches a maximum limit as the force increases to infinity and the integral of the tangent curve function is the energy [19, 20]. The tangent curve mathematical model is described in equation 1 as follows:

\[
F(x) = A \cdot (\tan(B \cdot x))^n
\]  

(1)

where \( F \) is the pressing force (kN), \( x \) is the deformation (mm), \( A \) is the force coefficient of mechanical behaviour (kN), \( B \) is the deformation coefficient of mechanical behaviour (mm\(^{-1}\)), \( n \) is the fitting curve function exponent (-).
**Figure 1.** Force and deformation curves of sunflower seeds at heat treatment temperatures.

**Table 6.** Tangent curve model coefficients and statistical analysis (mean ± standard deviation) at varying heat treatment temperatures.

| Temperatures (°C) | Tangent curve model coefficients | Statistical analysis |
|-------------------|----------------------------------|---------------------|
| Control 5.752     | 0.035                            | 0.0010              |
| ±0.235            | ±0.001                           | ±0.0002             |
| 40                | 6.298                            | 0.0008              |
| ±0.087            | ±0.001                           | ±0.0009             |
| 50                | 5.821                            | 0.0009              |
| ±0.127            | ±0.001                           | ±0.0007             |
| 60                | 5.984                            | 0.0009              |
| ±0.374            | ±0.001                           | ±0.0004             |
| 70                | 6.485                            | 0.0004              |
| ±0.231            | ±0.001                           | ±0.0006             |
| 80                | 6.818                            | 0.0020              |
| ±0.027            | ±0.001                           | ±0.0003             |
| 90                | 7.048                            | 0.0079              |
| ±0.026            | ±0.001                           | ±0.0029             |
| 100               | 7.227                            | 0.0073              |
| ±0.018            | ±0.001                           | ±0.0025             |

* Sunflower bulk seeds at room temperature of 25 °C, p > 0.05 level of significance or \( F_{critical} > F_{ratio} \) is significant.
Table 7. Tangent curve model coefficients and statistical analysis (mean±standard deviation) at 40 °C in relation to heating time.

| Heating time (min) | Tangent curve model coefficients | Statistical analysis |
|-------------------|---------------------------------|----------------------|
|                   | A (kN)  | B (mm l) | n     | F ratio | F critical | p       | R²     |
| *Control          | 5.752   | 0.035    | 1     | 0.0010  | 3.870      | 0.975   | 0.999  |
| ±0.235            | ±0.001  | ±0.0002  | ±0.004 | ±0.003  | ±0.001     | ±0.001 |
| 15                | 6.034   | 0.033    | 1     | 0.0038  | 3.863      | 0.951   | 0.999  |
| ±0.267            | ±0.001  | ±0.0006  | ±0.001 | ±0.004  | ±0.001     | ±0.001 |
| 30                | 6.102   | 0.034    | 1     | 0.0012  | 3.864      | 0.960   | 0.999  |
| ±0.202            | ±0.001  | ±0.0002  | ±0.001 | ±0.002  | ±0.001     | ±0.001 |
| 45                | 6.310   | 0.034    | 1     | 0.0012  | 3.865      | 0.974   | 0.999  |
| ±0.411            | ±0.001  | ±0.0011  | ±0.002 | ±0.013  | ±0.001     | ±0.001 |
| 60                | 6.551   | 0.035    | 1     | 0.0007  | 3.866      | 0.983   | 0.999  |
| ±0.447            | ±0.003  | ±0.0012  | ±0.002 | ±0.023  | ±0.001     | ±0.001 |
| 75                | 6.590   | 0.035    | 1     | 0.0011  | 3.865      | 0.974   | 0.999  |
| ±0.189            | ±0.001  | ±0.0006  | ±0.002 | ±0.007  | ±0.001     | ±0.001 |

p > 0.05 level of significance or F critical > F ratio is significant.

Table 8. Tangent curve model coefficients and statistical analysis (mean±standard deviation) at 100 °C in relation to heating time.

| Heating time (min) | Tangent curve model coefficients | Statistical analysis |
|-------------------|---------------------------------|----------------------|
|                   | A (kN)  | B (mm l) | n     | F ratio | F critical | p       | R²     |
| *Control          | 5.752   | 0.036    | 1     | 0.0010  | 3.870      | 0.975   | 0.999  |
| ±0.235            | ±0.001  | ±0.0002  | ±0.004 | ±0.003  | ±0.001     | ±0.001 |
| 15                | 7.575   | 0.035    | 1     | 0.0054  | 3.864      | 0.941   | 0.999  |
| ±0.203            | ±0.001  | ±4.6·10⁻⁵| ±0.003 | ±0.001  | ±0.001     | ±0.001 |
| 30                | 7.243   | 0.035    | 1     | 0.0087  | 3.864      | 0.933   | 0.999  |
| ±0.035            | ±0.001  | ±0.0090  | ±0.002 | ±0.041  | ±0.001     | ±0.001 |
| 45                | 7.197   | 0.035    | 1     | 0.0081  | 3.864      | 0.931   | 0.999  |
| ±0.111            | ±0.001  | ±0.0055  | ±0.002 | ±0.026  | ±0.001     | ±0.001 |
| 60                | 7.388   | 0.035    | 1     | 0.0113  | 3.863      | 0.916   | 0.999  |
| ±0.074            | ±0.001  | ±0.0039  | ±0.001 | ±0.015  | ±0.001     | ±0.001 |
| 75                | 7.598   | 0.036    | 1     | 0.0077  | 3.863      | 0.931   | 0.999  |
| ±0.201            | ±0.001  | ±0.0023  | ±0.001 | ±0.011  | ±0.001     | ±0.001 |

p > 0.05 level of significance or F critical > F ratio is significant.

4. Conclusion
Heat treatment temperatures significantly (p < 0.05) increased the deformation energy and percentage oil yield of sunflower bulk seeds compressed at a maximum force of 100 kN and speed of 5 mm/min. The interaction effects of heating time and heat treatment temperatures of 40 and 100 °C did not significantly (p > 0.05) decrease or increase the deformation energy and percentage oil yield. The analytical deformation energy amounts were within the range of the numerical energy values.
The coefficients of determination of the theoretical description of the experimental relationships between the force and deformation curves in relation to heat treatment temperatures and heating time were 0.999. The theoretical model coefficients were statistically significant ($p > 0.05$). The exponent of the tangent model representing the value of the fitting curve was found to be 1 in all analyses. It is important to mention that the use of the Statistica software [16] interprets the statistical significance when the $p$ value is less than the significance level or the $F_{\text{ratio}}$ greater than the $F_{\text{critical}}$ (Table 4). This is, however, contrary to the Mathcad statistical package [21] where the $p$ value is greater than the significance level or $F_{\text{critical}}$ greater than the $F_{\text{ratio}}$ (Tables 6 to 8).

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