Experimental Study on Heat Transfer of Alfalfa during the Vibration-Assisted Compression

Haoyi Wang, Pei Wu,* Haijun Du, Ruoyan Li, and Yanhua Ma

Compression alfalfa into briquettes is an effective way to solve the problem of storage and transportation. In the process of compression, heat is generated, which raises the temperature in the material. The appropriate temperature can improve the quality of alfalfa briquettes. In this paper, the effect of assisted vibration frequency, moisture content, and particle size on the compression temperature were tested. The results showed that when the vibration was applied, the material particle temperature in the mold rose significantly, and the core particle temperature rose faster than the edge temperature. The vibration frequency was the most significant factor affecting heat transfer in the three studied factors. When the moisture content and particle size were constant, the heat transfer effect increased first and then decreased with the vibration frequency, and it had an optimal value at 17 Hz. When the vibration frequency and particle size were constant, the heat transfer effect increased first and then decreased with the moisture content. It had an optimal value of 20%. The experimental results explained the effect of vibration frequency, moisture content, and particle size on temperature variation during alfalfa compression and provided a basis for reasonable process parameters.

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Keywords: Alfalfa; Vibration; Moisture content; Temperature; Compression

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INTRODUCTION

Alfalfa is a leguminous crop that has abundant crude protein, vitamins, and amino acids (Wang *et al*. 2003). It is a favorite forage for livestock (Wang *et al*. 2017; Vranic *et al*. 2018; Zhao *et al*. 2019). Due to the low bulk density of alfalfa, it takes up a lot of space during storage and transportation. Because the cost of handling and storing loose alfalfa is high, densifying it into briquettes is an efficient method of utilizing it (Fang *et al*. 2018). The loose material is compressed into briquettes under the action of mechanical pressure. During the compression, the temperature of the material in the die will increase. The proper temperature, such as the softening point of lignin, can reduce the maximum compression pressure, improving the quality of products. Therefore, the compression temperature and heat transfer characteristics have a significant impact on briquetting.

Research on temperature in compression process mainly has focused on three aspects: the temperature variation speed of material, product quality and physical property of the briquette during hot pressing, as well as the determination of hot pressing parameters (Chou *et al*. 2009; Tu *et al*. 2015; Gao *et al*. 2018; Yao *et al*. 2018); the distribution of friction heat and temperature in die and material during cold pressing; the influence of temperature on the biomass compression process performance (Du *et al*. 2011; De *et al*.

2014; Mikulandrić *et al*. 2016); the distribution of temperature in compressed material during ultrasonic vibration-assisted pelleting; and predicting relations between process variables (such as ultrasonic power) and temperature (Song *et al*. 2014; Tang *et al*. 2015; Zhang *et al*. 2016).

To improve the quality of biomass briquettes, densification with assisted vibration has been examined; vibration can reduce the compressive force and improve the quality of products (Wu *et al*. 2014; Ma *et al*. 2016). The assisted vibration is also beneficial to heat transfer (Wu *et al*. 2020). Furthermore, the influence of the assisted-vibration frequency, moisture content, and particle size of the alfalfa on heat transfer should be studied. These three factors affect the alfalfa compression (Wang *et al.* 2022). In this paper, the temperature for compressing the alfalfa with assisted vibration was studied to reveal the mechanism of vibration-assisted compression and to explain the effect of vibration frequency, moisture content, and particle size on temperature variation during alfalfa compression. The data provides a basis for reasonable process parameters.

EXPERIMENTAL

Materials

The biomass in this test was alfalfa (*Medicago sativa* L.), which was harvested in the suburb of Hohhot (Inner Mongolia, China). The material was dried to moisture contents of approximately 2.7% (dried) by a DHG-9140A drying oven (OLABO Company Ltd., Jinan, China). The material was pulverized into small particles using a 9RS-60 feed crumbling machine (Machinery Plant of Inner Mongolia Agriculture University, Hohhot, China), and the impurities were removed. To obtain different moisture contents, the crumbled raw alfalfa was added with water and mixed sufficiently to adjust the moisture content to 10%, 20%, and 33%. The moisture content of the alfalfa was obtained by calculating the ratio of the water weight contained and the total weight of the raw material according to the GB/T 36055 (2018) standard. The material was stored in plastic bags. The particle size of the material was divided into large, medium, and small grades though the standard sieves (8-, 12-, and 16-mesh, respectively) according to GB/T 5917.1 (2008).

Fig. 1. Bagged experimental material

Different material moisture contents will give rise to different specific heat capacities. The specific heat capacity of the material is an issue that may influence the temperature change in the compression process. Tests were carried out to find out whether the influence of material specific heat capacity was significant. The material specific heat capacity under three moisture contents were measured by JTKD-II thermal conductivity tester (JANTYTECH Ltd., Beijing, China). The results are shown in Table 1. Because the volume of material used in the compression test was small, the difference of the material specific heat capacity had no significant influence on temperature change. In the subsequent text, the material specific heat capacity would be considered as the same.

Table 1. List of Material Thermal Properties

Moisture Content	Thermal Conductivity (W/m·K)	Thermal Diffusivity (mm^2/s)	Density (kg/m^3)	Specific Heat Capacity (J/(m^3·K))
10.0%	0.1192	0.2413	433	1140.86
20.0%	0.1349	0.2503	466	1156.55
33.1%	0.1645	0.2656	487	1271.77

Experimental system

An experimental system designed in this study is shown in Fig. 2a. A cylindrical die with a channel diameter of 45 mm and a length of 120 mm was used to make briquettes from the materials. The compression piston was driven by a hydraulic drive and control system that could provide the compression speed of 2.16 mm/s.

The assisted vibration was generated by a crank-slider mechanism, in which the slider pushed the connecting bars and a ring flange that was connected to the ejector rod. Thus, the experimental material in the die was subjected to an axial vibration applied by the ejector rod from below, see Fig. 2b. The vibration device could provide vibration with amplitude of 1.5 mm and frequency range of 0 to 25 Hz.

To compare the effects of assisted vibration on compression of alfalfa, six Pt100 thermocouple temperature sensors (Shanghai Songdao heating sensor Co., Ltd, China, Nominal temperature 0 to 200 °C, LIN±0.1%) were employed for measuring the compression temperature. The signals were amplified by a temperature transmitter and detected simultaneously by a data acquisition board NI USB-6210 (National Instruments Company Ltd., Los Angeles, CA, USA), which was programmed in software LabVIEW2013 (National Instruments Company Ltd.) and logged into a computer.

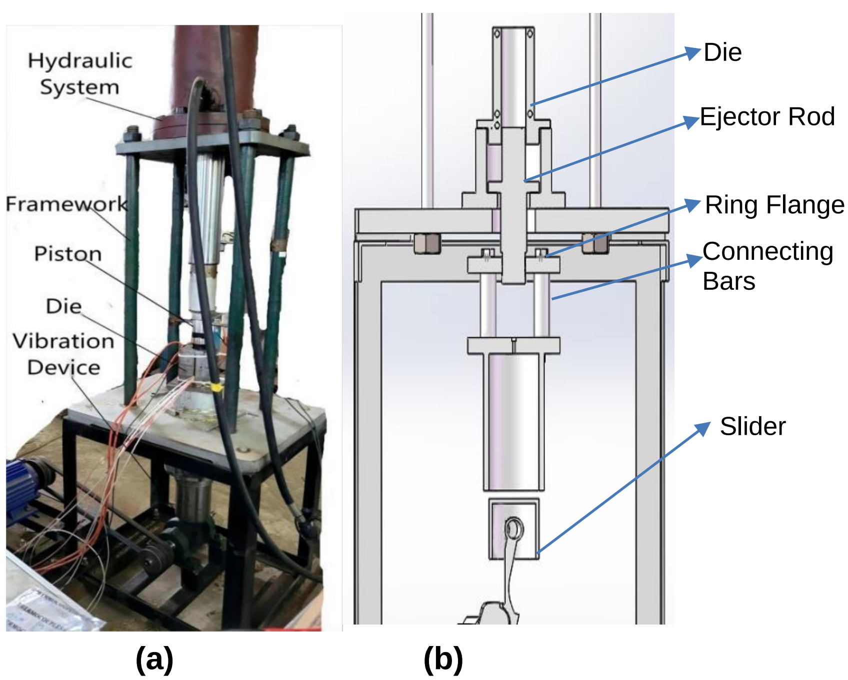

Fig. 2. (a) The experimental system; (b) the vibration device

Methods

The temperature of the die was kept at about 40 °C. Before compression, the die was heated by using a B/GXJ temperature-controlled silicon rubber heating sheet (Shanghai Songdao heating sensor Co., Ltd, China). The prepared alfalfa stalk particle of 10 g was put into the die, and two temperature sensors were placed in the bottom core and bottom edge of the material in the die. Next, 8 g of alfalfa stalk particle was added to the die, and then two temperature sensors were placed in the middle core and middle edge of the material in the die. Lastly, the rest of the 8 g alfalfa stalk particle was added to the die and two temperature sensors were placed in the upper core and upper edge of the die, as shown in Fig. 3. The sensors should be embedded in the material. When the initial temperature of the sensors was kept constant, the compression piston moved down, at the same time the vibration system started to work. Thus, a vibrated compression force was applied to the material in the die. During the tests, the temperature was measured and recorded by a data acquisition system programmed in LabVIEW2013 to computer. To study the influence of vibration on the compression temperature and its transmission in the briquettes, when the compression piston began to return, the assisted-vibration was stopped. A closed compression die was used in the test; the compression stroke was 80 mm.

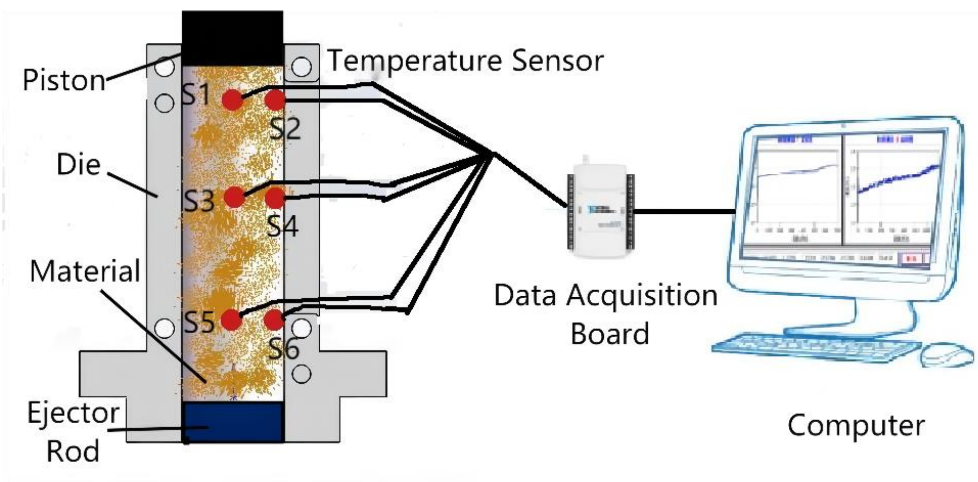

Fig. 3. Arrangement of the temperature sensors. S1, upper core; S2, upper edge; S3, middle core; S4, middle edge; S5, bottom core; S6, bottom edge temperature sensor

RESULTS AND DISCUSSIONS

Box-Behnken Test

The effect of moisture content, vibration frequency, and particle size and their interrelations on heat transfer during alfalfa compression were explored. The Box-Behnken response surface method was designed by Minitab 19 software (Minitab LLC, Philadelphia, PA, USA). Each parameter took 3 levels that were coded as 1 (High level), 0 (middle level), and -1 (low level). The moisture content is generally selected as 10% to 35% when the biomass material is compressed (Tumuluru 2014). The level of moisture content in this test was selected as 3 levels with 10% as low level, 20% as middle level, and 33% as high level. Because the vibration device could provide a frequency range of 0 to 25 Hz, the vibration frequency was selected as 0 Hz for low level, 10 Hz for middle level, and 20 Hz for high level. The large, middle, and small particle size alfalfa were set as low level, middle level, and high level, respectively. The list of parameters is shown in Table 2.

Table 2. List of Box-Behnken Test Parameters

Test Order Number	Moisture Content	Vibration Frequency	Particle Size
1	1	1	0
2	1	0	-1
3	-1	-1	0
4	-1	0	1
5	1	-1	0
6	0	1	1
7	0	0	0
8	0	-1	1
9	0	-1	-1
10	0	1	-1
11	0	0	0
12	-1	0	-1
13	1	0	1
14	-1	1	0
15	0	0	0

The temperature signal could be obtained by importing the test data into Origin2017 software (OriginLab, 2017, Northampton, MA, USA) and drawing the dot-line diagram. With and without assisted-vibration, the temperature change curve of alfalfa particles with time was different. The results are shown in Figs. 4 and 5.

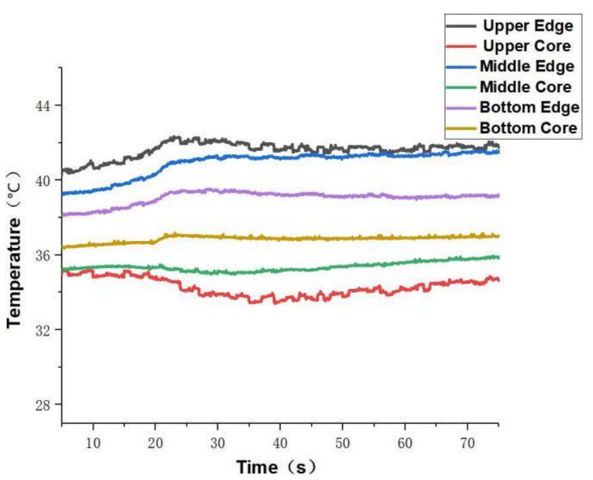

Fig. 4. Curve for the temperature without assisted-vibration compression (Moisture content middle level, Particle size high level)

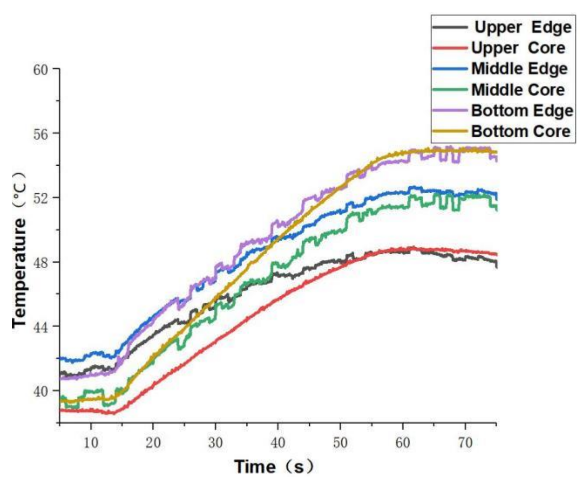

Fig. 5. Curve for the temperature with assisted-vibration compression (Moisture content middle level, Particle size high level)

When the alfalfa particle was compressed without assisted-vibration, no matter where the temperature sensor was placed in upper, middle, or bottom, the edge particle temperature was higher than the core temperature. Because the die surface temperature was higher than alfalfa particle, the heat transferred from hotter surfaces toward cooler material. In addition, as the compression stroke increased, the frictional sliding between edge particle and the die surface generated the heat. The heat was transferred from edge of the particle to core particle, and the temperature changed less than 4 ℃ in 75 seconds. When the assisted-vibration was applied to the compression, the temperature changed more than 8 ℃ in 75 seconds, and some places changed 14 ℃. Unlike the compression without vibration, assisted-vibration made the core particle temperature increase faster than the edge temperature. In bottom, the core particle temperature was initially lower than the edge temperature and finally it exceeded the edge temperature. This was attributed to the fact that the vibration was generated in the bottom of the die. These phenomena implied that vibration could make intense movement of the compressed material. Some bottom edge particles might move to the bottom core, and some bottom core particles might move to the middle core. This behaviour could promote heat transfer between particles. Moreover, collision caused by the vibration produced a large amount of heat. Thus, compression with assisted-vibration raised the core alfalfa stalk particle temperature faster.

To quantitatively analyze the influence of moisture content, vibration frequency, and particle size on heat transfer during alfalfa stalk particle compression, a specific index is needed to express the heat transfer effect. However, the temperature values measured by each sensor at each time point were different. It was inconvenient and inaccurate to compare these data points at different positions one by one. To eliminate the influence of time factor on temperature change, the curve drawn by the temperature sensor data was linearly fitted. The edge temperature was higher than the core temperature at the beginning regardless of any condition. Therefore, the edge temperature and the core temperature at the same height (upper, middle, and bottom of the die) were compared, and the slope difference of fitting line was taken as the heat transfer effect specific index. When the slope difference of temperature curve fitting line was positive, the heat transfer effect was not ideal. When the slope difference of the fitting line was negative, the heat transfer effect was ideal, as shown in Fig. 6. The data of 6 temperature sensors in 15 times Box-Behnken test were analyzed and compared at the same height, and the results are shown in Table 3.

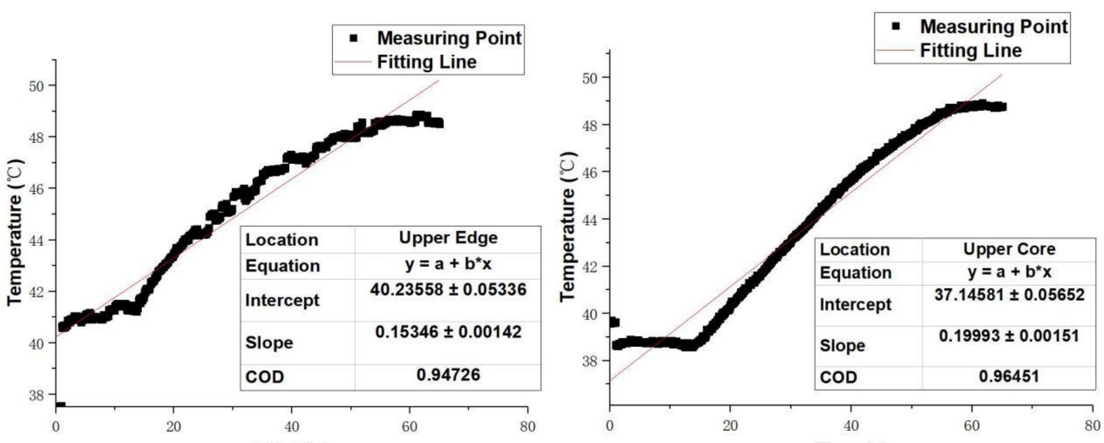

Fig. 6. Measuring point and fitting lines located in upper of the die under test order No.6 (Moisture content middle level, Vibration frequency high level, Particle size high level)

The slope differences of upper, middle, and bottom of the die were taken as the responses respectively to perform variance analysis (ANOVA) on the test results. The results of variance analysis are shown in Tables 4, 5, and 6.

Table 3. Box-Behnken Test Results

Test Order Number	Moisture Content (A)	Vibration Frequency (B)	Particle Size (C)	Upper Slope Difference	Middle Slope Difference	Bottom Slope Difference
1	1	1	0	-0.04962	-0.08179	-0.03566
2	1	0	-1	-0.03781	-0.06382	0.01844
3	-1	-1	0	0.01492	0.02344	0.02183
4	-1	0	1	-0.02995	-0.06311	-0.00965
5	1	-1	0	-0.00613	0.00034	-0.00252
6	0	1	1	-0.04647	-0.03389	-0.03827
7	0	0	0	-0.05566	-0.08044	-0.06035
8	0	-1	1	-0.00521	-0.00725	-0.00033
9	0	-1	-1	0.01267	-0.00656	0.00320
10	0	1	-1	-0.03752	-0.07728	-0.04367
11	0	0	0	-0.04433	-0.08425	-0.06136
12	-1	0	-1	0.02687	-0.03435	-0.04463
13	1	0	1	-0.04418	-0.05024	-0.01745
14	-1	1	0	-0.07148	-0.03346	-0.01763
15	0	0	0	-0.04592	-0.09210	-0.08160

Table 4. ANOVA of Box-Behnken Test in the Upper of Die

Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Model*	9	0.010789	0.001199	4.91	0.047
Linear Term*	3	0.007899	0.002633	10.79	0.013
A	1	0.000762	0.000762	3.13	0.137
B**	1	0.006124	0.006124	25.11	0.004
C	1	0.001013	0.001013	4.15	0.097
Square Term	3	0.001773	0.000591	2.42	0.181
A*A	1	0.000313	0.000313	1.28	0.308
B*B	1	0.000475	0.000475	1.95	0.222
C*C	1	0.001217	0.001217	4.99	0.076
Interactive Term	3	0.001117	0.000372	1.53	0.316
A*B	1	0.000460	0.000460	1.89	0.228
A*C	1	0.000636	0.000636	2.61	0.167
B*C	1	0.000020	0.000020	0.08	0.786

R^2=89.84%, R_{adj}^2=71.56%. Note: ** shows the factor is very significant ($P < 0.01$), * shows the factor is significant ($P < 0.05$)

Adj SS: Adjust sum of square. The sum of squares represents a measure of variation or dispersion of the mean distance. The calculation method is the sum of the squares of the difference from the mean. The adjust sum of square does not depend on the order in which the factors are entered into the model.

Adj MS: Adjust mean square. The mean square is calculated by dividing the adjust sum of square by the degrees of freedom.

F-value: Variance ratio. The value of dividing the variance of the two groups of samples.

P-value: P-value refers to the probability that the statistical summary is the same as the actual observation data in a probability model, or even greater.

According to the analysis of variance, the model was basically significant at the upper, middle, and bottom of the die. At any height, the vibration frequency was a significant factor to the heat transfer. At different positions, the influence of moisture content and particle size on the heat transfer was different. Sometimes the square term of moisture content was significant.

Table 5. ANOVA of Box-Behnken Test in the Middle of Die

Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Model*	9	0.017044	0.001894	8.75	0.014
Linear Term**	3	0.008048	0.002683	12.39	0.009
A	1	0.000969	0.000969	4.48	0.088
B**	1	0.006985	0.006985	32.27	0.002
C	1	0.000095	0.000095	0.44	0.538
Square Term**	3	0.007902	0.002634	12.17	0.010
A*A*	1	0.001559	0.001559	7.20	0.044
B*B**	1	0.006570	0.006570	30.35	0.003
C*C	1	0.000547	0.000547	2.53	0.173
Interactive Term	3	0.001093	0.000364	1.68	0.285
A*B	1	0.000159	0.000159	0.74	0.430
A*C	1	0.000448	0.000448	2.07	0.210
B*C	1	0.000486	0.000486	2.24	0.194

R^2=94.03%, R_{adj}^2=83.28%
Note: ** shows the factor is very significant (P < 0.01), * shows the factor is significant (P < 0.05);

Table 6. ANOVA of Box-Behnken Test in the Bottom of Die

Symbol	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value
Model*	9	0.011634	0.001293	4.31	0.061
Linear Term	3	0.003118	0.001039	3.47	0.107
A	1	0.000021	0.000021	0.07	0.803
B*	1	0.003097	0.003097	10.33	0.024
C	1	0.000000	0.000000	0.00	0.985
Square Term*	3	0.007231	0.002410	8.04	0.023
A*A*	1	0.003987	0.003987	13.30	0.015
B*B*	1	0.002576	0.002576	8.59	0.033
C*C	1	0.001721	0.001721	5.74	0.062
Interactive Term	3	0.001286	0.000429	1.43	0.338
A*B	1	0.000010	0.000010	0.03	0.862
A*C	1	0.001256	0.001256	4.19	0.096
B*C	1	0.000020	0.000020	0.07	0.807

R^2=88.59%, R_{adj}^2=68.04%
Note: ** shows the factor is very significant (P < 0.01), * shows the factor is significant (P < 0.05);

The heat transfer at the upper part of the die was analyzed first. The influence of particle size on heat transfer was higher than moisture content. When the moisture content and vibration frequency were constant, small particles could make heat transfer better. Because the air in the die gradually decreased with the densification of the alfalfa briquette during the compression process, particles had greater contact area to contact or collide with each other. This facilitated heat transfer between particles. If the particles were small, it would receive more vibration and had more opportunity to contact with each other. Therefore, the heat transfer was also better when the particles were densified. The moisture content with smallest significance was taken as middle level, and the influence of vibration frequency and particle size on the heat transfer at upper of the die was explored. The response surface map and contour map are shown in Fig. 7.

In the process of alfalfa stalk compression with assisted-vibration, the heat transfer at upper of the die increased with the increase of the vibration frequency, and increased first and then decreased slightly with the decrease of particle size. When the vibration frequency was 20 Hz and particle size was small, the heat transfer was ideal.

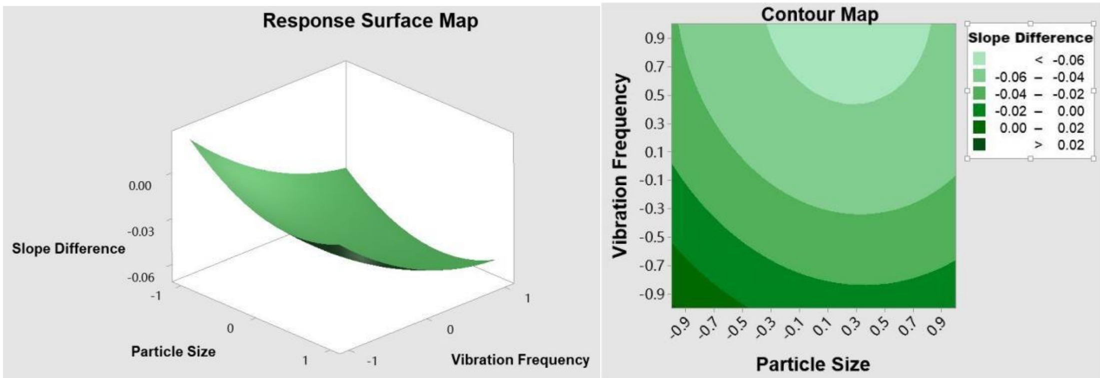

Fig. 7. Influence of vibration frequency and particle size on heat transfer at the upper of the die

The heat transfer at the middle and bottom of the die were analyzed. The influence of moisture content on heat transfer was higher than particle size. When the particle size and vibration frequency were constant, the moisture content of alfalfa stalk affected the fluidity of particles. If the moisture content was too high, the viscosity of the briquette was large, and the fluidity between particles would be reduced during the compression process. Thus, the heat transfer was not ideal. Moreover, the high moisture content made the material particles too viscous, which increased the maximum compression force during the compression process. It was not conducive to the life of compression equipment and reduction of energy consumption. The springback of the briquette after extrusion was also large. If the moisture content was too low, the viscosity was reduced, and the fluidity between particles was slightly improved. However, the water film between particles was less, but the air content in the pores between particles was more. The thermal conductivity of air is very low and not conducive to heat transfer between particles. When the moisture content was too low, the reduced viscosity made the briquette loose, and the drop resistance decreased. It was also not ideal for the quality of products. Therefore, the particle size with smallest significance was taken as middle level, and the influence of vibration frequency and moisture content on the heat transfer at middle and bottom of the die was explored. The response surface map and contour map are shown in Fig. 8 and Fig. 9.

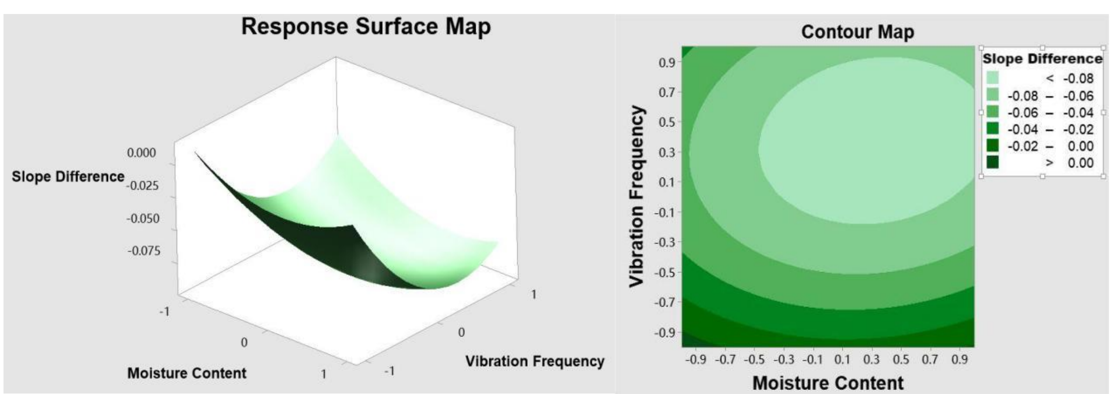

Fig. 8. Influence of vibration frequency and particle size on heat transfer at the middle of the die

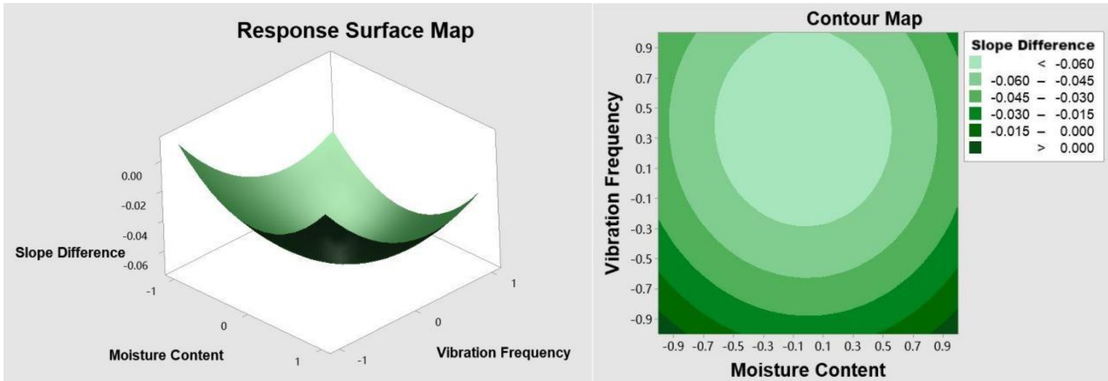

Fig. 9. Influence of vibration frequency and particle size on heat transfer at bottom of the die

In the process of alfalfa stalk compression with assisted-vibration, the heat transfer at the middle of the die increased rapidly with the increase of vibration frequency, and then decreased slightly. With the increase of moisture content, the heat transfer first increased and then decreased. According to the contour map, when the vibration frequency was 14 Hz and the moisture content was 23%, the heat transfer had a better effect.

For the heat transfer at the bottom of the die in the process of alfalfa vibration compression, the vibration frequency and moisture content were increased first and then decreased. When the vibration frequency was 15 Hz and the moisture content was 18%, the heat transfer effect was optimal.

Based on the aforementioned analysis of the heat transfer at the upper, middle, and bottom of the die during the vibration compression process of alfalfa stalk particle, when the vibration frequency was 14 to 20 Hz, the moisture content of alfalfa stalk particles was 16% to 23%. The particle size was small, and the compressed alfalfa stalk briquette would have a good heat transfer effect during compression process.

CONCLUSIONS

1. Vibration frequency, moisture content, and particle size influenced heat transfer during alfalfa stalk particle compression. When the alfalfa particle was compressed without assisted vibration, the particle temperature at edge of the die was higher than at core during the whole process. The heat in the die was transferred from edge particle to core particle. However, when the alfalfa particle was compressed with assisted-vibration, the particle temperature at core of the die was lower than at edge first, and then the particle temperature at core increased rapidly and gradually exceeded the particle temperature at edge. The particle temperature at core of the die could be close or even higher than the particle temperature at edge finally. Moreover, the particle temperature at bottom of the die was higher than other places because the vibration was generated in the bottom of the die, which resulted in more movement and heat.
2. The slope difference of fitting a straight line of particle temperature at edge and at core at the same height was analyzed under different conditions. The Box-Behnken test was used to obtain the significance of moisture content, vibration frequency, and particle size. The vibration frequency was the most significant factor affecting heat transfer at any case during alfalfa stalk particle compression.

3. Through response surface analysis and contour map, the influence of three factors on heat transfer at different heights in the die was obtained. For the optimal effect of heat transfer during alfalfa stalk particle compression, the vibration frequency was 14 to 20 Hz, the moisture content of alfalfa stalk particles was 16% to 23%, and the particle size was small.

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