

Design of High Moisture Alfalfa Drying Experimental Bench and Thermodynamic Simulation of Drying Process

Peng Wang [1], Haitang Cen [1,*], Penghui She [1], Jianguo Qin [1], and Risu Na [1]

[1] School of Mechanical Engineering, Inner Mongolia University of Technology, Hohhot, 010051 China

* 1054949591@qq.com

Abstract. In the process of alfalfa modulation, the problems of long drying time and serious nutrient loss have been the constraints. In order to solve these problems, this study optimised the drying process of high moisture alfalfa whole bales by designing a high moisture alfalfa drying test bed and performing thermodynamic simulation of the drying process. Specifically, the upper and lower inserted hot-air needle mechanisms and the blower-suction device were designed. In order to verify the validity of the design, FLUENT was used to simulate the high moisture alfalfa bale with 40% moisture content under different working conditions. Through the response surface method, the optimum working parameters were determined to improve the efficiency of the whole drying process. The optimum drying parameters were finally determined as: temperature 90°C, air velocity 4.646 m/s and drying time 20 min.

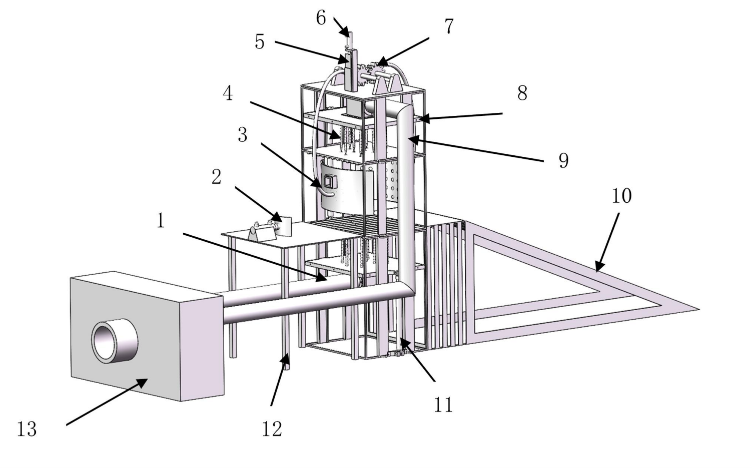
Keywords: High-moisture alfalfa; Blast-suction device; FLUENT; Response surface method; Drying time.

1. Introduction

Currently, alfalfa produced in China is of low quality, so the domestic demand for high-quality alfalfa mainly relies on imports. However, the cost of importing alfalfa is high, so there is an urgent need to develop alfalfa drying equipment in China to meet the domestic market demand for high quality alfalfa. The traditional method of drying alfalfa is mainly air-drying, but this method is likely to lead to serious loss of alfalfa stems and leaves, which in turn affects the nutrients and quality of alfalfa. Therefore, in order to produce high quality alfalfa, high moisture baling technology is needed. High-moisture baling can avoid the loss of alfalfa nutrients, so as to ensure that the dried alfalfa meets the high quality requirements. In terms of bale shape, round bale has the characteristic of tight outside and loose inside, which is suitable for baling when alfalfa has high moisture, and can greatly retain the nutrients of alfalfa to ensure that the dried alfalfa is of good quality. Therefore, the research and development of equipment suitable for high moisture alfalfa drying is of great significance to improve the quality of domestic alfalfa [1,2,3].

2. Improved design of alfalfa bale drying process

The high-moisture alfalfa bale drying experimental bench consists of three parts: upper and lower insertion drying mechanism, air blower-suction mechanism and air blower mechanism, which are shown in Fig. 1. The interfaces of upper and lower insertion drying mechanism and air blower-suction mechanism are connected with the multi-channel ducts of the multi-energy complementary hot air system mentioned before, so that the multi-energy complementary hot air system is able to deliver hot air to the upward and downward insertion drying mechanism and the blower-suction mechanism through the multi-channel ducts. The whole process consists of placing high moisture alfalfa hay bales on the working table by means of a forklift truck, and pushing the hay bales to the drying position by means of a hydraulic lever. Subsequently, hot air syringes of the upper and lower insertion drying mechanisms are inserted into the high-moisture alfalfa bale. At the same time, the blower-suction mechanism lands through the control system to surround the high moisture alfalfa bale, initiating the operation of the multi-energy complementary hot air system. Once the moisture content of the alfalfa hay bales is reduced to 17%, the upper and lower insertion drying mechanisms and the blower-extraction mechanism will return to their initial positions, and the hay-pushing device pushes the dried hay bales away from the table. At this point, it waits for a forklift to transport it to the warehouse, ready for the start of the next drying cycle [4,5].

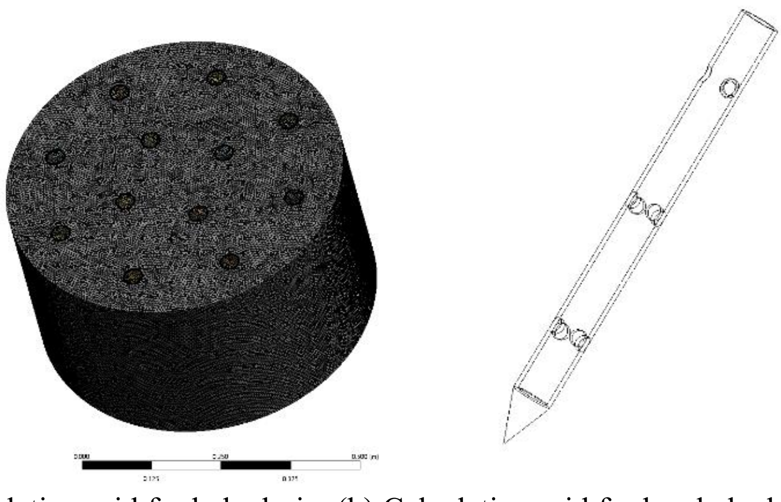


1- Lower insertion drying mechanism; 2- Grass pushing device; 3- Negative pressure moisture absorbing cover; 4- Hot air syringe; 5- Straight rack; 6- I hydraulic rod; 7- Straight rack; 8- Rectifier; 9- Upper insertion drying mechanism; 10- Grass pushing device; 11- II hydraulic rod; 12- Grass releasing table; 13- Air blower system.

Fig. 1 Diagram of alfalfa drying equipment

3. Porous media modelling of circular hay bales

Pre-processing software was used to perform polyhedral meshing of the fluid domain inside the cylindrical hay bale, 24 hot air needles and the hot air needle tube [6,7]. In domain meshing, 5103211 nodes and 968497 meshes were obtained. In order to reduce the computational burden of the computer during meshing and considering that the hay bale is an axisymmetric solid, only half of the mesh is required. An example of the corresponding mesh division for the forage drying model is shown in Figure 2-(a) [6,7]. The hot air syringe has an inner diameter of 12 mm, an outer diameter of 15 mm and a height of 345 mm. there are circular holes distributed around the circumference of the hot air syringe in three layers. In the first layer, there are three circular holes with a diameter of 12 mm uniformly arranged in the circumferential direction; in the second and third layers, there are four circular holes with a diameter of 12 mm uniformly arranged in the circumferential direction in each layer. The 3D model of the hot air syringe is shown in Figure 2-(b) [8,9,10,11].



(a) Calculation grid for bale drying(b) Calculation grid for hay bale drying

Fig. 2 Three-dimensional model of hay bale drying

4. Response surface methodology optimisation

4.1 Determination of factors and levels

This paper focuses on the effects of temperature, wind speed and time on the moisture content of high-moisture alfalfa hay bales [12,13,14,15]. The simulation results were analysed and found that the drying process of alfalfa has inhomogeneity, i.e. some positions of the bale dry faster, while some positions of the bale dry slower [16].

In order to simplify the experiment and improve the ease of operation, the average moisture content of the hay bales was chosen as the response value. In terms of experimental design, the three factors that have a greater influence on the average moisture content, namely temperature, wind speed and time, were selected as independent variables, and a three-factor, three-level experimental design was carried out using Design-Expert 13 software. The specific experimental factors and level information are shown in Table 1.

Table 1. Response surface test factors and levels

Level	Considerations		
	Temperature (℃)	Air Velocity (m/s)	Timing (min)
-1	80	3	15
0	90	4	20
1	100	5	25

4.2 Response surface test

The average moisture content of alfalfa hay bales dried for a certain time can be obtained through the post-processing software CFD-POST of ANSYS. According to the response surface test factors and levels, the design of the response surface is shown in Table 2.

Table 2. Response surface design and results

Experiment Number	A	B	C	Y Average Moisture Content (%)
1	-1	-1	0	5.836
2	1	-1	0	4.971
3	-1	1	0	5.464
4	1	1	0	2.314
5	-1	0	-1	6.362
6	1	0	-1	5.212
7	-1	0	1	4.482
8	1	0	-1	0.054
9	0	-1	-1	5.994
10	0	1	-1	5.654
11	0	-1	1	4.634
12	0	1	1	0.084
13	0	0	0	2.484
14	0	0	0	2.832
15	0	0	0	3.211
16	0	0	0	3.451
17	0	0	0	3.992

Using the software Design-Expert 13 to analyse the analysis of variance of the test of the average moisture content of bales for a certain period of time of the hot-air blasting of the bales, the quadratic polynomial regression equation obtained is: Y = 3.19-1.20A-0.9865B-1.75C-0.5645AB-0.8195AC-1.05BC + 0.6984A2 + 0.7624B2 +0.1369C2.

The results of the ANOVA of the regression model are presented in Table 3 and the P-value of the model is less than 0.0003 indicating that the model is significant. The P-value of the misfit term is 0.7630, which is greater than 0.05, indicating that the equation is well fitted. The coefficient of determination (R2) is 0.9643, indicating that the correlation between the actual and predicted values is high. Therefore, the model can better reflect the relationship between the factors and response surface values of high moisture alfalfa hay bales in the drying process and can predict the optimal process conditions. From the P-values, it can be learnt that temperature (A), wind speed (B), time (C) and the interaction term BC have highly significant effects (P-value less than 0.01) on the average moisture content of high-moisture alfalfa hay bales. Comparison of the F-values led to the conclusion that the order of influence of the three factors on the average moisture content of high moisture alfalfa bales was: time > temperature > wind speed, i.e., time had the most significant effect on moisture content, followed by temperature, and lastly, wind speed.

Table 3. regression model variance

Source Of Variance	Degrees Of Freedom	Square Sum	Mean Square	F-value	P-value	Significance
Mould	56.96	9	6.33	21.02	0.0003	**
A	11.44	1	11.44	37.99	0.0005	**
B	7.79	1	7.79	25.85	0.0014	**
C	24.39	1	24.39	80.99	<0.0001	**
AB	1.27	1	1.27	4.23	0.0787	
AC	2.69	1	2.69	8.92	0.0203	
BC	4.43	1	4.43	14.71	0.0064	**
A^2	2.05	1	2.05	6.28	0.0348	
B^2	2.45	1	2.45	8.13	0.0247	
C^2	0.0789	1	0.0789	0.2621	0.6245	
Residual	2.11	7	0.3011			
Lost Proposal	0.7630	3	0.2543	0.7565	0.5738	
Pure Error	1.34	4	0.3362			
Aggregate	59.06	16				
R^2	0.9643					
R^2_{Adj}	0.9184					

Note: * is significant difference (P<0.05); ** is highly significant difference (P<0.01).

Figure 3 is a contour and response surface plot showing the effect of interaction between factors on the average moisture content of high moisture alfalfa hay bales, produced by Design-Expert 13 software. In the figure, the horizontal projection of the response surface plot is the contour line, and the steepness reflects the effect of the factors on the moisture content, with a greater steepness indicating a more significant effect. Combined analysis of the contour and response surface plots revealed a significant interaction between wind speed and time (p-value less than 0.01) and insignificant interactions between the other factors. When considering the factors individually, time had the most significant effect on moisture content, followed by temperature, while wind speed had a relatively small effect [17,18].

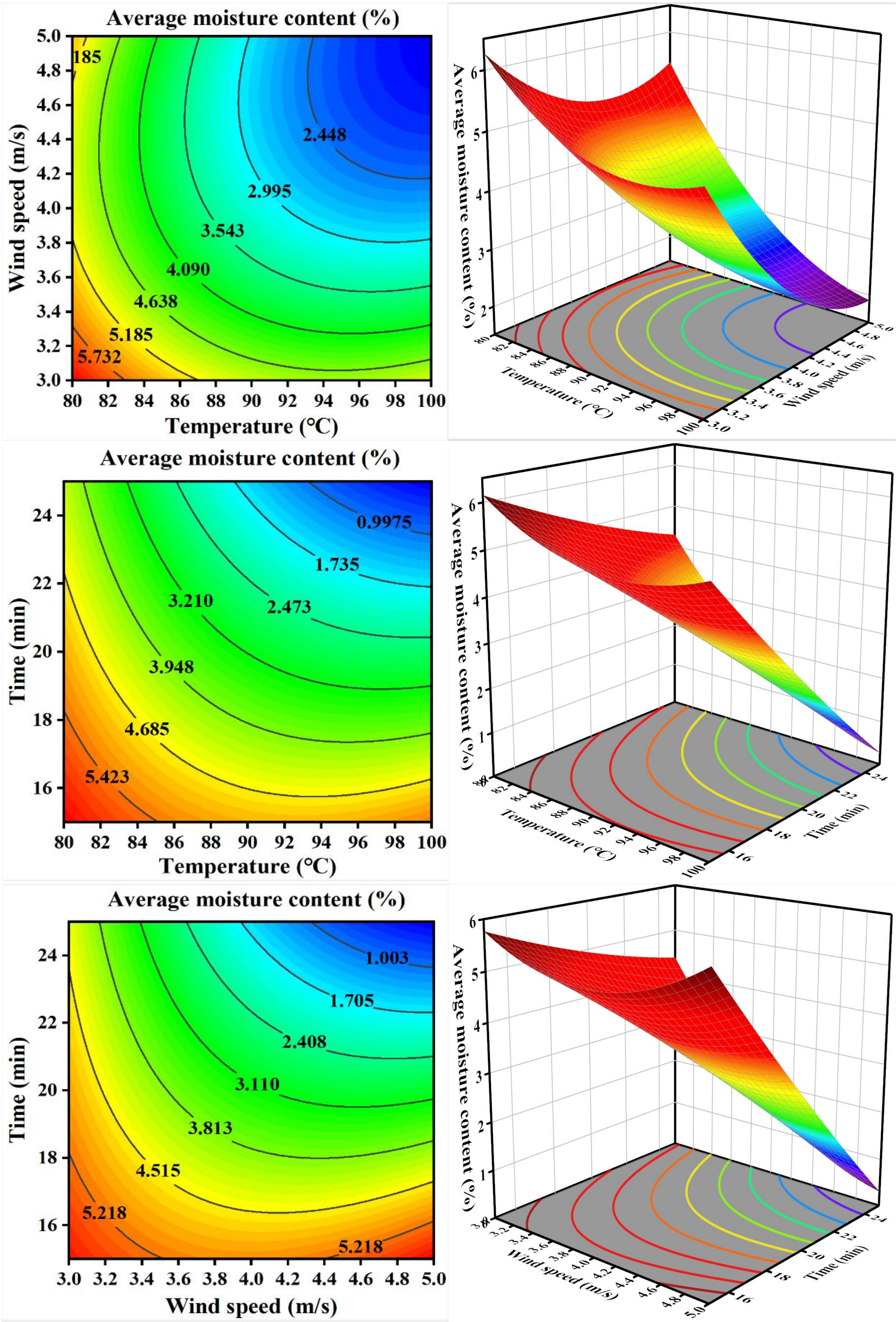
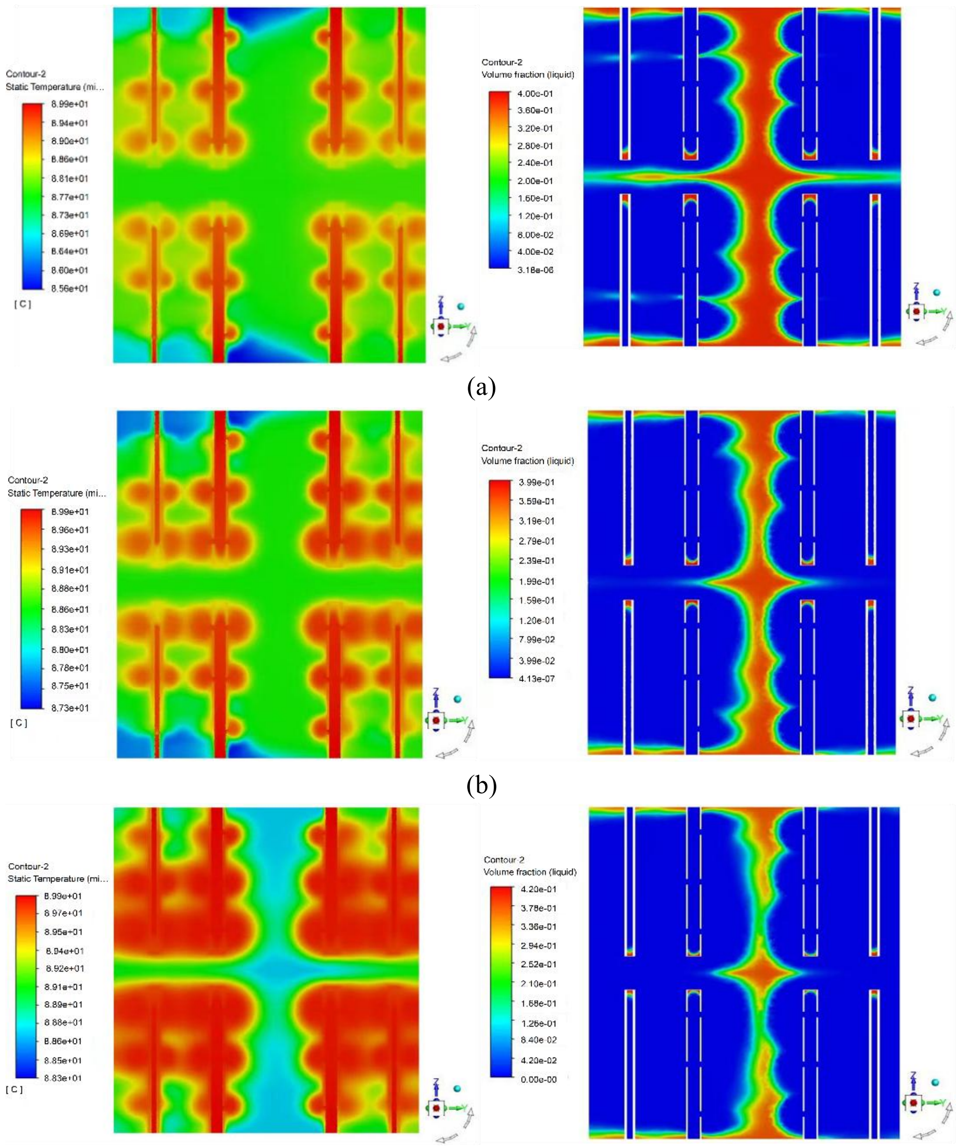


Fig. 3 Contour plots and response surface plots of the interaction between the three factors on the average moisture content of high moisture alfalfa hay bales

Optimisation of the experimental data by means of the Design-Expert 13 software allowed the prediction of the optimal drying of high-moisture alfalfa bales. Considering that too high drying temperature may lead to internal "carbonisation" phenomenon, the drying temperature of 90℃ was selected. According to Fig. 4, the optimal combination of process parameters was 90°C, 4.646 m/s air speed and 20 minutes drying time. Under these conditions, the average moisture content of high-moisture alfalfa bales was expected to be 2.873% [19,20,21,22].

In determining the optimum process conditions, we required that the maximum moisture content of alfalfa hay bales not exceed 17%. After selecting the temperature of 90°C, wind speed of 4.6 m/s, and time of 20 minutes as the optimal process parameters, simulations were carried out using FLUENT software to verify the results, which are shown in Fig. 4. With the increase of drying time, the temperature of the bales increased and the moisture content decreased, and finally reached below 17%. Fig. 4-(c) shows that the temperature at the side orifice of the hot air syringe is 99.9°C and 89.9°C in other areas. The CFD-POST analysis yielded an average moisture content of 3.033% for the bales after 20 minutes of drying. The error was 5.6% compared to the predicted optimal process parameters. Therefore, the simulation results indicate that the selected optimal process parameters are reliable [23].



(a) (b) (c)

Fig. 4 Cloud diagram of temperature and moisture content distribution in the computational domain at 100°C and 4m/s for the 10th-20th min.

5. Summary

(1) This paper describes the necessity of drying high moisture alfalfa whole bale, discusses the alfalfa whole bale drying process, and improves its design. The upper and lower insertion drying mechanism and the blower-suction device are designed to improve the efficiency and quality of whole bale drying. On this basis, a whole bale drying experimental table was designed.

(2) In this study, high moisture alfalfa hay bales under different working conditions were simulated and analysed, and the data obtained from the simulation were used to carry out an in-depth study by applying the response surface method. In the case of single factor, the degree of influence of time, temperature and wind speed on drying time is in the following order: time>temperature>wind speed. Especially, the interaction between wind speed and drying time is the most significant. Through the application of response surface methodology, the optimal working parameters for drying high moisture alfalfa hay bales under different working conditions were successfully determined, i.e., temperature of 90 ℃, wind speed of 4.6 m/s, and time of 20 min, under which the drying effect was optimal.

(3) The simulation validation results showed that the final moisture content of alfalfa hay bales was 16.8% under the working conditions of temperature 90℃, wind speed 4.6m/s, and time 20min, which meets the safe storage conditions of hay bales, and the error of the average moisture content was only 5.6%. This proved the reliability of the optimum process parameters predicted by the response surface method. This provides theoretical support for the drying of high-moisture alfalfa whole bales and effectively improves the nutritional quality of the forage.

Acknowledgments

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