APPLICATION OF AUTOMATIC CONTROL FURNACE FOR COMBUSTION OF BIOMASS BRIQUETTE FUEL FOR TOBACCO CURING

by

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Applying biomass energy for curing flue-cured/Virginia tobacco heating is the best way to realize green tobacco production. Aiming to satisfy the heating demand for flue-cured tobacco curing, a new heating device that uses biomass briquettes as fuel for curing tobacco is adopted the first time, which was developed using modern mature electromechanical and computer technology. The new device consists of automatic feeding, ash cleaning, ventilation, and ignition systems governed by an intelligent tobacco-curing controller designed for specific curing characteristics. The results of experiments conducted with an original direct combustion coal furnace, bulk curing barn, and controlled coal-fired heating indicated that the heat supply of the new device could satisfy the heat demand during the tobacco curing process, with a good performance-controlling difference of ±0.5 °C between the actual and target dry-bulb temperature in the barn. With its unattended heating management and use of fully burning fuel, the new device sharply decreased the cost of manual operation and tobacco leaves required per kilogram compared to a coal furnace. Considering the shape of its structure, the new device could be used to heat homes or small-scale boilers if the chip procedure of the controller is altered.

Key words: *agricultural energy, drying device, clean energy, energy efficiency, biomass*

Introduction

Tobacco curing (TC) is the key link to ensuring and solidifying the quality of flue-cured/Virginia tobacco [1], which accounts for more than 80% of the energy used in the production process [2]. Coal direct combustion is widely used for heating since over a century in China, with low combustion efficiency and serious environmental pollution [3]. As the largest flue-cured tobacco producer in the word, China annually utilizes 3-4 million tons of coal for TC [4]. As people continually become more aware of environmental protection, especially in the last two years, the opinions against this production mode of flue-cured tobacco have become increasingly strong [5]. Although emissions of polluted air from coal is reduced after physical desulfurization-utilizing an efficient raw chemical material-firing coal for tobacco heating is a waste of this non-renewable resource [6].

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As a recognized clean energy source, biomass fuels such as firewood have traditionally been used to cure tobacco in some flue-cured tobacco producing countries, such as Brazil, Zimbabwe, Cambodia, and others in the region [7, 8]. In this way, some production areas use biomass briquette fuel (BBF) with ∅ 32-100 mm to provide heat for flue-cured tobacco by direct burning instead of coal combustion [9]. However, some of the gasification gases produced by BBF in the coal-fired furnace are not burned and are discharged into the atmosphere via the chimney. This waste of fuel results in a high cost for TC [10]. Through a massive data analysis, Bortolini *et al.* [11] found a feasible way for greening the tobacco flue-curing process using BBF. Recently, Ren *et al.* [12] tested the efficiency and cost-effectiveness of an existing agricultural BBF furnace to demonstrate its feasibility for flue-cured tobacco heating.

To utilize the gasification gases of BBF, Xiang *et al.* [13] designed a direct-fired BBF heating equipment for incorporating pyrolysis and gasification, which achieved a high fuel-utilization rate. For improving the utilization efficiency of biomass fuel calorific value, we previously introduced [14] an integrated combustion/gasification furnace for firewood and BBF. However, there is still room to improve the thermal efficiency of biomass fuel according to the results of this data analysis. Even with the rapid development of artificial intelligence [15], the present heating processes of BBF such as fuel ignition (or firing), ash removal, and uninterrupted fuel addition are still dependent on manual operations.

To reduce the curing labor of fueling, Henderson [16, 17] made the first attempt to automatically control the dry-bulb temperature (DBT) in the barn and used a device with a special material to expand after heating and contract after cooling. This device enabled controlling the size of the fuel valve by pulling the lever to control the oil fuel supply. Moore Jr. [18] first invented an automatic temperature control instrument called a *limit control* which can be set to 26.67-82.22 °C on the intelligent control device. Thus, the heat supply of the fuel oil furnace can be effectively controlled. It was not until 1976 that the structure and technology of bulk curing were sufficiently mature to intelligently control the DBT and wet-bulb temperature (WBT) in the barn using an electrical device [19]. The aforementioned research on DBT control methods was aimed at liquid oil fuel, however, the operation mode and equipment construction of solid fuel are different from those of liquid fuel in the TC process.

To resolve the mentioned problems, namely, the lower thermal efficiency of BBF and the increasing labor cost in TC, in this work a new type of intelligent control furnace was developed utilizing modern mature electromechanical and computer technology.

Materials and methods

Equipment design and construction

The automatic control furnace (ACF) for BBF combustion includes feeding, ash cleaning, ventilation, and automatic ignition systems and matching intelligent tobacco-curing controller, figs. 1 and 2. The outer dimensions are 1050 mm (length) × 270 mm (width) × 390 mm (height).

The feeding system consists of a fixed feeding box – 2, a round BBF-feeding passage – 3, a feeding motor – 5, a double-helix drive rod – 20, and a BBF push outlet – 30. The gears in the transmission protection device – 4 at the end of the double-helix drive rod – 20 mesh the feeding motor – 5 in the round BBF-feeding passage – 3 to transmit power, and the BBF is quantitatively pushed from the feeding box – 2 to the furnace according to the TC needs.

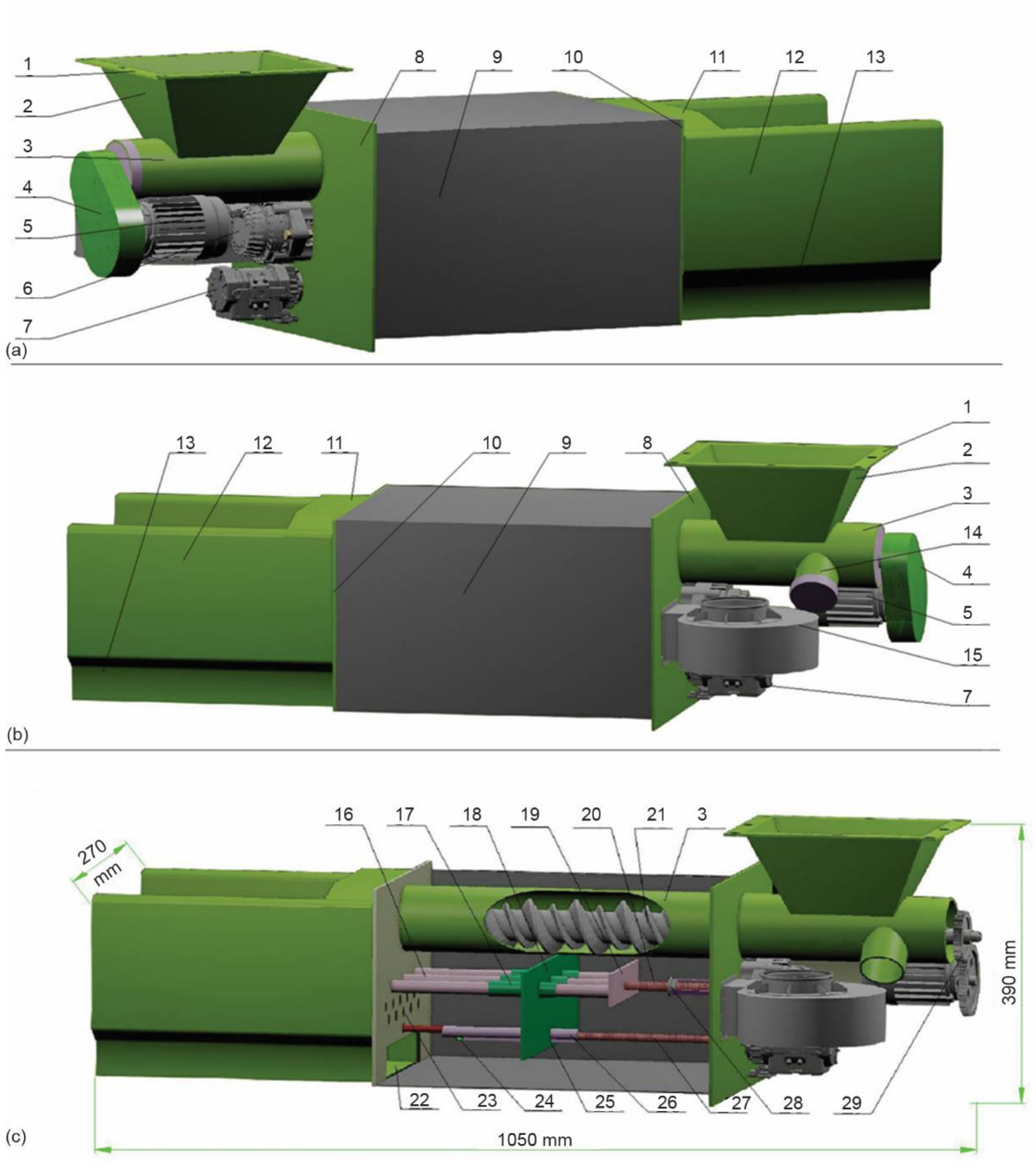

Figure 1. Outline and internal structure of equipment: (a) left view, (b) right view, and (c) profile of ventilation flow chamber; *1 – flange end (connecting additional bigger box), 2 – feeding box, 3 – round BBF-feeding passage, 4 – transmission protection device, 5 – feeding motor, 6 – ash-cleaning motor, 7 – ignition motor, 8 – outer sealing baffle, 9 – ventilation chamber, 10 – inner sealing baffle, 11 – furnace cap, 12 – furnace outer wall, 13 – furnace base, 14 – maintenance door on round feeding passage, 15 – blower, 16 – poker, 17 – circular hollow steel bushing, 18 – functional board, 19 – fixed plate for pokers, 20. double-helix drive rod, 21. screw transmission rod, 22 – bottom ventilation entrance, 23 – vertical outlet for combustion-supporting air, 24 – infrared detector, 25 – slide way in functional board, 26 – ignition rod, 27 – screw transmission rod for ignition rod, 28 – power conversion device, 29 – transmission gear*

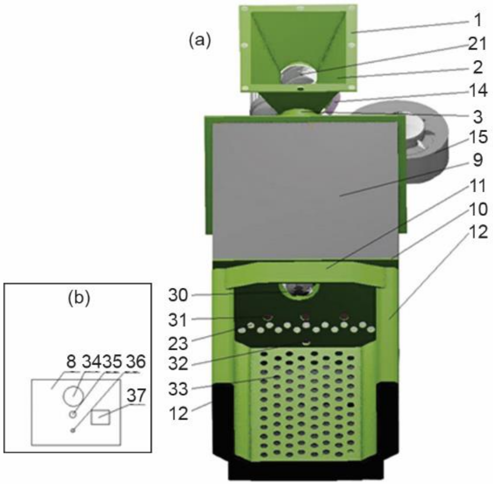

Figure 2. Furnace structure and hole of outer sealing baffle; (a) overhead view and (b) hole diagram of outer sealing baffle, *30 – BBF push outlet, 31 – outlet for the poker, 32 – outlet for the ignition rod, 33 – level outlet for combustion-supporting air (many), 34 – hole for round biomass-feeding passage, 35 – hole for power conversion device, 36 – hole for screw transmission rod, 37 – hole for blower*

From front to back, the ash cleaning system consists of an ash-cleaning motor – 6, a power conversion device – 28, a screw transmission rod – 21, a fixed plate for pokers – 19, a circular hollow steel bushing – 17, pokers – 16, and outlets for the pokers – 31. Likewise, a functional board – 18 is fixed on the inner wall of the ventilation chamber – 9. When ash needs to be cleaned, the ash-cleaning motor – 6 rotates and pulls the fixed plate for pokers – 19 through the power conversion device – 28, above which the multiple poker – 16 slides back and forth through the circular hollow steel bushing – 17 in the functional board – 18, and is extended out from the outlet for the poker – 31 into the furnace to push the ash forward, so as to achieve the purpose of cleaning. When it is not necessary to clean up the ash, the poker – 16 retreats to the ventilation chamber – 9 to avoid contact with the high temperature. The frequency and magnitude of the several extensions of the pokers – 16 are affected by the amount of biomass fuel supplied during the TC process.

In synchronization with the feeding system, the external air is blown into the ventilation chamber – 9 through the blower – 15. Under the addition of pressure, part of the combustion-supporting air enters the furnace base – 13 through the bottom ventilation entrance – 22, then to the level outlet for combustion-supporting air – 33 into the furnace to provide solid BBF burning, and at the same time the other part through the vertical outlet for combustion-supporting air – 23 provides oxygen for the gasification gas combustion. This oxygen supply method can preheat the combustion-supporting air while reducing the temperature of the ventilation chamber – 9. This not only reduces the ambient temperature of the equipment in the ventilation chamber – 9, but also reduces the heat loss from the outer sealing baffle – 8.

The ignition rod – 26 is connected to the screw transmission rod for the ignition rod – 27 and rotates under the driving of the ignition motor – 7 through the slide way in functional board – 25 on the functional board – 18 and moves forward to insert into the BBF reactor in the furnace from the outlet for the ignition rod – 32. When BBF is fired by an internal electric hot spot in the ignition rod – 26, the infrared detector – 24 will detect the combustion of fuel in the furnace, and the intelligent tobacco-curing controller controls the ignition system to return it to its original position.

Heat supply calculation

Since 2009, China has been building large-scale bulk curing barns with unified structures and coal-fired heating equipment, fig. 3, and now has a total of 800000-900000 barns. At present, approximately 5000 kg of fresh tobacco leaves are loaded on hanging bamboo poles per batch per barn, and the average amount of coal consumed is 1 ton.

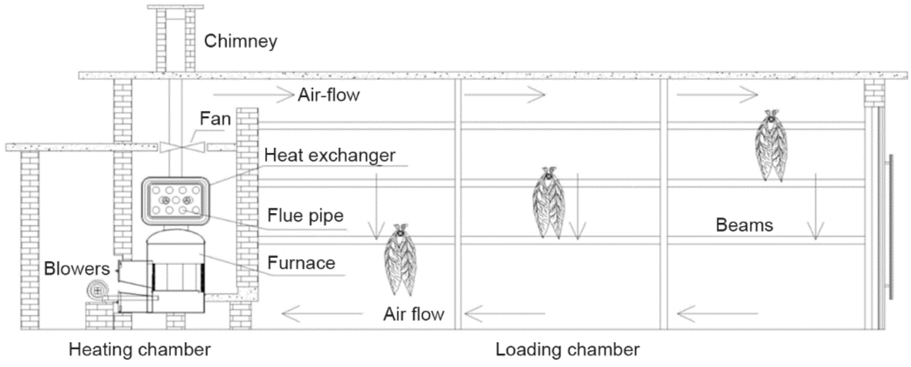

Figure 3. Internal structural profile of a bulk curing barn and coal-fired heating equipment

Feeding motor required maximum speed

The amount of fuel required varies at different stages during the TC process. Fuel supply per unit time during the TC process is mainly affected by the tobacco leaf moisture discharge. To maintain DBT required in the barn, energy for air exchange inside and outside of the barn, and to substitute for the heat loss from the wall to the environment, is provided. Therefore, the maximum moisture drainage period is also the maximum speed period of the feeding motor for N (rps):

$$N = \frac{W}{SD\rho Q} \tag{1}$$

where W [kJs^{-1}] is the maximum heat requirement per curing batch per barn in the TC period [14], S [m^2] – the effective discharge cross-sectional area of the round BBF-feeding passage, D [mr^{-1}] – the distance of fuel push per turn of the double-helix drive rod, ρ [kgm^{-3}] – the density of BBF, and Q [kJkg^{-1}] – the calorific value of dry-based BBF.

The TC procedure is also a process of constant warming and temperature stabilization. To ensure the quality of TC, the actual DBT in the curing barn should be in accordance with the target DBT. For the constant change of biomass fuel supply, the corresponding speed of the feeding motor should be changed at 1/5N-N (rps). According to the differences between the actual and target DBT of ~0.5 °C, 0.5-0.2 °C, 0.2-0.2 °C, –0.2-0.5 °C, and –0.5 °C, the speed of the feeding motor is correspondingly set to 1/5N (rps), 2/5 N (rps), 3/5 N (rps), 4/5 N (rps), and N (rps), respectively.

Calculation of oxygen supply for combustion

The BBF combustion equation

The usual reference for the typical volume of any gas in 1 mol is approximately 22.4 L at temperature 0 °C and pressure 101.325 kPa:

$$\mathrm{C}_x\mathrm{H}_y\mathrm{S}_z\mathrm{O}_w + \left(x + \frac{y}{4} + z - \frac{w}{2}\right)\mathrm{O}_2 + 3.78\left(x + \frac{y}{4} + z - \frac{w}{2}\right)\mathrm{N}_2 \rightarrow$$

$$\rightarrow x\mathrm{CO}_2 + \frac{y}{2}\mathrm{H}_2\mathrm{O} + z\mathrm{SO}_2 + 3.78\left(x + \frac{y}{4} + z - \frac{w}{2}\right)\mathrm{N}_2 + \mathrm{Q} \tag{2}$$

where $C_xH_yS_zO_wN_n$ is the molecular formula of all BBF, in which the formation of nitrogen oxides is too small, therefore it is considered to convert into N_2 during combustion, whose subscript values of *x*, *y*, *z*, and *w*, are determined by chemical detection.

The actual air volume of BBF combustion is derived using eq. (5)

$$\mathrm{G_b} = \mathrm{C}_x + \mathrm{H}_y + \mathrm{S}_z + \mathrm{O}_w = 12x + 1.008y + 32z + 16w \tag{3}$$

$$V_\mathrm{th} = \frac{22.4 \cdot 4.78\left(x + \dfrac{y}{4} + z - \dfrac{w}{2}\right)}{12x + 1.008y + 32z + 16w} \tag{4}$$

$$V_\mathrm{a} = \alpha V_\mathrm{th} \tag{5}$$

where G_b [g] is the weight of BBF, V_{th} [Lg^{-1} or m^3kg^{-1}] – the theoretical air volume of biomass combustion, V_a [m^3kg^{-1}] – the actual air volume of biomass combustion, and α – the excess air coefficient obtained by changing the feed rate of combustion-supporting air and detecting the relationship between the fuel and SO_2, NO_x concentration and smoke emission temperature [20]. Finally, according to eq. (5), the feed motor is matched with BBF supply to the furnace, and the speed of the blower is matched.

The system thermal efficiency of the bulk curing barn is η [%], which is calculated using eq. (6)

$$\eta = \frac{(m_\mathrm{f} - m_\mathrm{d})c_w}{m_\mathrm{b}Q}100\% \tag{6}$$

where m_f [kg] is the weight of the fresh leaves per curing batch per barn, m_d [kg] – the weight of dry leaves, m_b [kg] – the weight of BBF that is consumed for TC, and c_w ($2.6 \cdot 10^3$ kJ/kg) is the average heat of vaporization for a leaf during the normal curing process [4], which is usually calculated when DBT is 50 °C [21].

Working principle

The working principle of the combustion-supporting intelligent tobacco-curing controller is illustrated in fig. 4. At the beginning of TC, the curer sets the specific values of the target DBT and WBT and the heating speed on the controller using the keys. Then, the controller starts detecting the actual DBT in the loading chamber of the bulk curing barn through the DBT and WBT sensor and calculating the existing temperature difference between the target DBT setting and the actual DBT. The controller governs the speed of the feeding motor of the feeding system to transport BBF into the furnace according to this difference, and the blower speed of the ventilation system is synchronously matched. At the same time, the infrared detector detects in ACF that there is no flame in the furnace and feeds this information back to the controller, which manages the ignition device that extends into BBF in the furnace and conveys electrical power to the ignition rod, in which the heating wire ignites BBF. The infrared detector detects when fuel burns and feeds this information back to the controller, which draws the ignition device back to the original position. Then, during the TC process, the controller calculates the difference between the target DBT setting and the actual DBT every five seconds and continues to regulate the feeding and ventilation systems. In the same way, the WBT is controlled by the dehumidification system in the controller.

If the fire in the furnace is extinguished during TC process, it will be detected by the infrared detector, and the feedback into the controller will start the ignition system again. According to the different raw materials of biomass fuel, the working time of the ash cleaning system can be set using the controller, which automatically records the number of turns of the screw transmission rod in the feeding system and controls the frequency and magnitude of the pokers in BBF reactor.

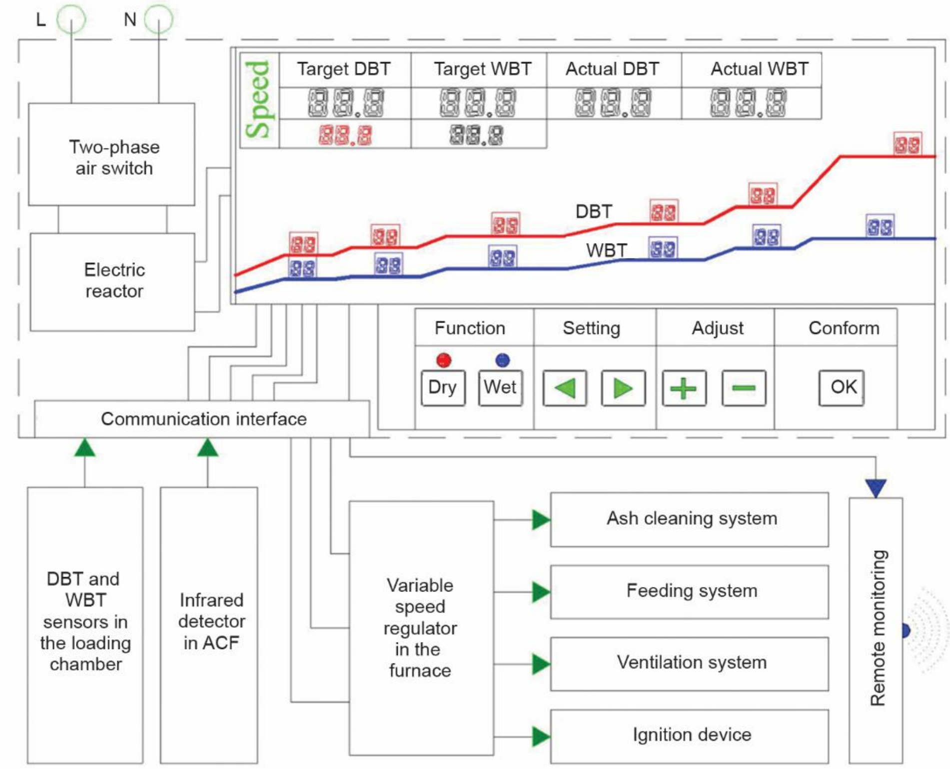

Figure 4. Control operation diagram of the intelligent controller

Test verification

Experiments were carried out from June to August 2019 in Shuangmiao Xuchang, Wangcun Luoyang, and Duguan Sanmenxia, all in Henan Province. Tobacco fields with uniform fertility and flat terrain were selected. The middle mature tobacco of 100 varieties were collected after fixed poles using rope were loaded into the curing barn, and the loading capacity per curing batch per barn was controlled at 5000±50 kg. The BBF with length 30-50 mm, ∅ 0.8 mm and density 1.20 g/cm^3 was produced by crushing the tobacco stalks collected from the tobacco field.

The structure and heating equipment of the downward air-flow bulk curing barn in fig. 4 were adopted. After removing the grate and refractory of the original coal-fired heating equipment, the furnace of ACF can be used in the original coal-fired furnace through the coal feeding door. One was barn BBF using ACF, with the furnace of ACF inserted into the coal-original furnace by the coal-fired furnace door, sealed and fixed. The other was barn coal using coal according to the original coal-burning operation mode. To reduce the experimental error, tobacco leaf harvesting, pole arrangement, loading density, and curing start were carried out simultaneously.

Detection method

The quality of the fresh and dried tobacco per curing batch per barn was measured by taking representative leaves. Electricity and fuel consumption were recorded during the experiments. The operating costs for the TC were equal to the local labor cost per unit time multiplied by the number of people required to fuel the furnace and remove the ash.

A digital thermometer (Handian HX-209, Dongwan, China), with frequency recorded every 10 minutes, was employed to measure DBT at the sampling points in the bulk curing barn during TC process.

The TC process comprises three stages: yellowing, color fixing, and dry leaf vein. The corresponding key DBT points that retain longer residence time are 38 °C, 48 °C, and 68 °C, respectively [22], which are beneficial to detection.

When DBT in the experimental barn was at 38 °C, 48 °C, and 68 °C, and the fuel burned steadily, referring to the literature [23], the concentration of flue gas discharged from the chimneys was measured at the central position of the chimney outlet using the automatic gas tester (TW-3200, Tuowei Qingdao China).

The 3D-Max 2013 software was used in drafting, while the GraphPad Prism 5.0 software analyzed the experimental data and the system thermal efficiency was calculated using eq. (6).

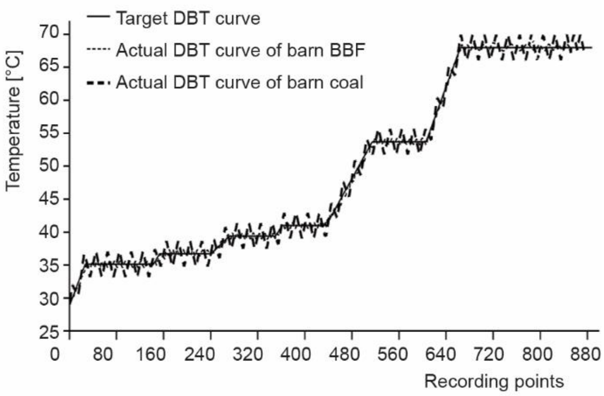

Figure 5. Variation of DBT in the two-fuels barns during TC process

Results and discussion

Matching the degree between heating supply and DBT requirements

Figure 5 shows the change in DBT between the setting target and actual results in tobacco middle leaf curing in two fuel types of curing barns. The fluctuation of the DBT curve in barn BBF deviates from the preset target DBT curve less than in barn coal and is closer to the setting target curing curve. The difference in data shows that the difference between the actual and target DBT is in the range of ±0.5 °C in barn BBF, which is smaller than the range of barn coal at ±1.5 °C. The results show that the actual DBT in barn BBF can be well-controlled by technicians when they operate the heating equipment with two different heat sources.

Comparative analysis of chimney gas

Under the same external temperature, the contents of gas components discharged from chimneys at the key temperature points are shown in tab. 1. The differences in chimney outlet temperature, O_2, CO, and CO_2 during the heating process are apparent. The CO is the product of insufficient hydrocarbon combustion, whose content in barn BBF is between 0.6% and 1.4%. This is much lower than the content for the same type of barn coal, and lower than the range of 1.1% to 2.1% as we previously reported for TC heating [14]. However, in their system, the oxygen needed for the gasified gas combustion of BBF was supplied by natural ventilation. This difference shows that the design of ACF using a ventilation system controlled by the intelligent tobacco-curing controller is more reasonable.

Table 1. Quantity of gas emissions from chimney exit at the key TC stages

Temp. points	Treatments	Gas temperature [°C]	O_2 [%]	CO [‰]	CO_2 [%]	NO_x [mgm^{-3}]	SO_2 [mgm^{-3}]
38 °C	Barn BBF	95.3±1.9	9.7±0.4	1.4±0.5	8.4±0.7	6.2±0.2	426.3±33.4
	Barn coal	135.6.2±3.6	14.1±0.1	8.8±1.1	6.2±0.3	40.5±14.9	841.2±95.6
48 °C	Barn BBF	146.5±4.8	12.1±0.5	1.2±1.4	5.8±0.5	5.1±1.6	398.1±40.7
	Barn coal	185.4±5.7	15.8±0.2	10.9±1.4	4.2±0.8	37.8±11.5	799.5±74.5
68 °C	Barn BBF	155.1±4.1	13.3±0.3	0.6±0.7	5.1±0.3	4.6±0.32	385.4±25.1
	Barn coal	191.2±7.0	16.9±0.6	7.1±1.8	3.9±0.6	31.4±3.7	716.2±69.3

Economic benefit analysis of equipment operation

From tab. 2, it can be seen that under the condition of BBF surplus in the feeding box, ACF eliminates the manual operation links of fuel fire and the frequent addition and management of the furnace. It not only intelligently controls the heating demand of fuel firing, but also successfully realizes the unattended TC mode, the same as using a liquid burner for TC by some other countries. The manual operation cost of ACF is significantly reduced with our method. Combined with tab. 1, we can see that barn BBF burns well. Although the calorific value of two different types of fuel has little difference, BBF consumption of barn BBF is lower than that of barn coal. In terms of an economic benefit analysis, although the power consumption of barn BBF is 20-30 kWh higher than that of barn coal, the total cost of tobacco leaves per batch per barn is similar between in barn BBF and barn coal, and the cost of dry tobacco per kg is 0.4 US$ lower as well. According to eq. (6), the system thermal efficiency values of the two pieces of heating equipment are 54.75% and 41.03%, respectively.

Some countries use an oil burner for TC heating [24]. The burner injects fire by insetting a heat exchanger into a bulk curing barn whose connection mode is similar to that of ACF and whose furnace could inset into another furnace. Therefore, ACF could be used as a solid fuel burner to extend to flue-curing tobacco production areas with abundant biomass resources.

Table 2. Comparison of the curing details, cost, and system thermal efficiency during the TC process

	Barn BBF	Barn coal
Curing time [hour]	142	145
Maximum fuel loading [kg]	150	50
Maximum fire keeping time [hour]	–	6
Green tobacco quality per batch each barn [kg]	5010	4975
Dry tobacco quality per batch each barn [kg]	752	748
Operating cost for labor curing [US$]	4.30	51.55
Power consumption [kWh per barn per batch]	175	148
Fuel consumption [kg]	1200	1250
Total cost [US$ per barn per batch]	17.72	201.34
Curing cost per kg dry tobacco [US$ per kg]	0.23	0.27
System thermal efficiency [%]	54.75	41.03

Note: "–" is automatic continuation. According to local market prices in 2019, coal after desulfurization was 108.83 US$/t, BBF was 128.88 US$/t, and electricity was 0.09 US$/kWh. The calorific value of BBF and coal are 16850 kJ/kg and 21428 kJ/kg, respectively.

Conclusion

In this study, we used modern mature technology to create a new heating device for TC that manages the entire BBF fire during the heating process intelligently. The test results indicated that within a range of ±0.5 °C between the actual and target DBT, the new device performs well on matching DBT requirements for TC heating supply through procedural control. By programmed machinery government replacing manual operation and with the fuel fully burning, the new device sharply decreased the cost of TC labor and tobacco leaves per kilogram compared to the conventional coal-fired device. Considering the structure of the new device is similar to light and heavy oil burners in terms of direct heating by connecting sockets, there is potential for use in home heating or small-scale boilers by changing the chip procedure of the intelligent tobacco-curing controller. This is a promising direction for future research and can be further developed for more efficiency and increasing the range of applications of this technology.

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