RESEARCH ON ENERGY SAVING AND EMISSION REDUCTION FOR RURAL TOBACCO CURING

by

Enhai LIU[a*], Wenyun ZHANG[a], Xiaoyang GAO[b], Zhanghui GUO[a], and Biao QI[a]

[a] School of Petroleum Engineering, Changzhou University, Changzhou, China
[b] Xuhui Design Co., Ltd., Zhengzhou, China

Original scientific paper
https://doi.org/10.2298/TSCI2303771L

This paper proposes a novel technology for waste heat recovery from a coal-fired curing barn flue gas, which can reduce simultaneously the flue gas pollutants. The upper and lower shed tobacco leaves are used as the research object during the curing of tobacco leaves in the rural curing tobacco house. The temperature and the humidity are monitored during the curing process, the change in the appearance of the tobacco leaves is observed. The desulfurization and de-nitration system can improve the uniformity of the overall tobacco leaves temperature and humidity, and can realize the integration of waste heat recovery of coal-fired boilers and flue gas pollutants treatment. An experiment is carried out and the results show that the technology can save energy to the greatest extent while ensuring the quality of tobacco leaves.

Key words: *uniform heating, flue-cured tobacco, applied mathematics, waste heat recovery*

Introduction

At present, individual tobacco farmers in China generally use the coal-fired curing technology to cure tobacco leaves, which requires a large amount of fossil fuels with a low heat utilization rate. The burning of fossil fuels produces a large amount of flue gas containing sulfides and NO_x during the annual curing process, which aggravates the environmental pollution. In addition, the temperature and humidity are unevenly distributed during the curing process, resulting in different quality of the tobacco leaves after curing. Li, *et al.* [1] analyzed the relationship between pigment content and hue value during the tobacco leaf curing process. Li, *et al.* [2] used a dynamic model to fit the brightness value, red-green value, yellow-blue value and other data of the tobacco leaves during the air-curing process to obtain the yellowing law of the tobacco leaves. Ding, *et al.* [3] measured the physiological indicators and color indicators of the tobacco leaves during the curing process to reveal the color change law. Li, *et al.* [4] studied experimentally the influence of different wet bulb temperatures on the various indicators of tobacco leaves in the middle of the leaf. Some scholars also studied the effects of curing methods on tobacco leaf components for in-depth study on the temperature stabilization time, humidity, and main chemical changes during the yellowing period of tobacco leaves [5-8]. In recent years, many experts and scholars conducted energy-saving optimization studies on heat pump technol-

* Corresponding author, e-mail: liuenhai1018@126.com

ogy and biomass-energy-cured tobacco. However, heat pumps were suitable for large-scale tobacco curing, and the flue gas emissions after curing cannot be effectively treated. Although the use of biomass energy to cure tobacco leaves had certain effects on improving the environment and reducing the greenhouse effect, the calorific value during the curing process cannot be controlled, and the cost of raw materials was relatively high [9-12]. However, there was little research on the integrated design of improving the uniformity of the overall tobacco temperature and humidity, the waste heat recovery of coal-fired boilers and the treatment of flue gas pollutants in the coal-fired curing barn used by individual tobacco farmers. This research focuses on the analysis of physical changes, coal consumption and theoretical heat recovery during the process of curing tobacco in the coal-fired curing barn. A three-effect filter desulfurization and denitration system is proposed. and it is suitable for an economical operating system for energy saving and emission reduction in coal-fired curing barn, which helps to improve the uniformity of the overall tobacco leaf temperature and humidity, and realizes the integration of waste heat recovery of coal-fired boilers and the treatment of flue gas pollutants.

Cured tobacco leaves

The tested fresh tobacco leaves (the cured variety) were taken from the tobacco production base in Central China and harvested in due course. In order to study the curing of tobacco leaves in a conventional coal-fired curing barn, the temperature and humidity of the upper and lower sheds were tracked for four days (August 13-16, 2016) at fixed points (9:00, 15:00). The temperature and humidity change curves in the curing barn were shown in figs. 1 and 2, respectively.

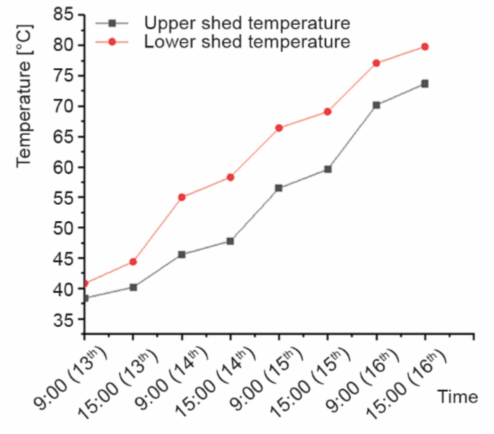

Figure 1. The temperature in the curing barn change with time

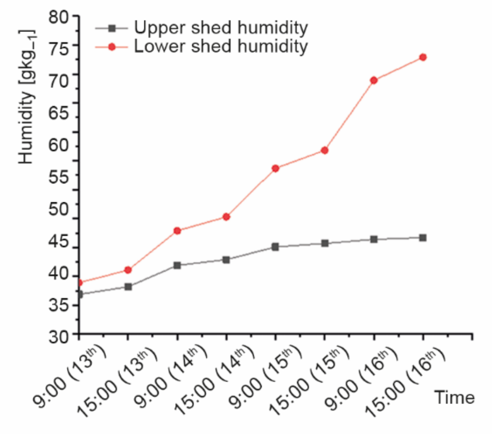

Figure 2. The humidity in the curing barn change with time

According to fig. 1, the temperature of tobacco leaves increased with time, and the temperature of the lower shed was obviously higher than that of the upper shed as a whole. The temperature difference between the upper and lower sheds was 2.4-10.5 °C. The temperature difference between the second day and the third day was larger than the temperature difference between the first day and the fourth day. According to fig. 2, as the curing time increased, the humidity in the upper shed gradually stabilized, and the humidity in the lower shed gradually increased for a longer time. As the humidity value increased, the humidity difference between the upper and lower sheds would gradually increase, the humidity difference was 2-31.2 g/kg, indicating that the lower shed tobacco leaves evaporative more moisture than those in the upper shed. It could be concluded from figs. 1 and 2 that when the curing barn was heated, the temperature and humidity in the upper and lower sheds were not uniform, which caused the tobacco leaves in the lower shed to mature faster than those in the upper shed.

According to the roasting process of tobacco leaves, the color change rate of the tobacco leaves was relatively slow in the early stage of curing, and the color of the tobacco leaves does not change significantly. After 24 hours, the tip of the tobacco leaves began to turn yellow. As the baking time increased and the temperature increased, the moisture content in the tobacco leaves decreased, and the tobacco leaves appeared sharp and curled. The color of the tobacco leaves gradually changed within 24-60 hours. The color was in the transitional period between the green of fresh tobacco leaves and the yellow in the late baking period, and the color purity was small, indicating that the hue value in the tobacco leaves gradually decreased.

After curing, only the lower shed tobacco leaves were qualified. The lower shed tobacco leaves were taken out and the upper shed tobacco leaves was heated again until they were cooked. The result showed that the upper shed tobacco leaves ash became brown due to secondary heating, which reduced the industrial applicability of the tobacco leaves. It could be seen that temperature and humidity determined the sensory quality of tobacco leaves.

Coal consumption and heat recovery

The roasted tobacco leaves consumed 1750 kg of coal, and the cured tobacco leaves emitted 45500 kg of CO_2, 42 kg of SO_2, and 12.25 kg of NO_x. The tobacco leaf roasting was carried out 8 times a year, so the annual coal consumption was 14000 kg, that means that 364000 kg of CO_2, 336 kg of SO_2, and 98 kg of NO_x will be emitted. It can be seen that coal consumption and emissions of major pollutants are huge.

The theoretical heat recovery could be calculated [13]:

$$Q = \rho c m \Delta t \tag{1}$$

where Q [kJs^{-1}] is the heat, ρ = 1.2 kg/m^3 – the air density, c = 1.013 kJ/kg°C – air's specific heat, Δt – the temperature difference between the inlet and outlet air, and the average value was 9.5 °C.

According to eq. (1), every unit mass of hot air is to recover the heat of 11.5482 kJ/s.

The recovered heat per hour is:

$$Q = 11.5482 \times 3600 = 41573.52 \text{ kJ/h} \tag{2}$$

The recovered heat per hour is:

$$Q = 41573.52 \div 4.185 = 9933.93548 \text{ kcal/h} \tag{3}$$

The recovered heat is equivalent to 1.419 kg/h of standard coal, which means that 1.419 kg of standard coal can be saved per hour, 34.056 kg of standard coal can be saved per day, and CO_2 emissions can be reduced by 36.894 kg, SO_2 – 0.034 kg, and NO_x – 0.009 kg per hour.

Coal-fired flue gas waste heat recovery and desulfurization and de-nitration system

Energy saving and emission reduction have been catching much attention in society and academy, devices for energy harvesting [14, 15] and technology for heat consumption estimation [16] are widely used in engineering, and there are many mathematical models to study the thermal efficiency [17-21].

In order to realize the energy saving and emission reduction of coal-fired curing barn, we design a system for waste heat recovery [22], desulfurization [23] and de-nitration [24] of coal-fired curing barn flue gas. It can improve the uniformity of the overall tobacco temperature and humidity in the coal-fired curing baring, and realize the integration of waste heat recovery of coal-fired boilers and treatment of flue gas pollutants. This system mainly includes a waste heat recovery in coal-fired boilers and a curing barn, a device for uniformly heating the tobacco leaves, and a desulfurization and de-nitration filter device. When the curing barn cures the tobacco, it realizes the recovery of the radiant heat released from the boiler furnace to the environment. The diagram of the flue gas desulfurization and de-nitration system of coal-fired flue gas house is shown in fig. 3.

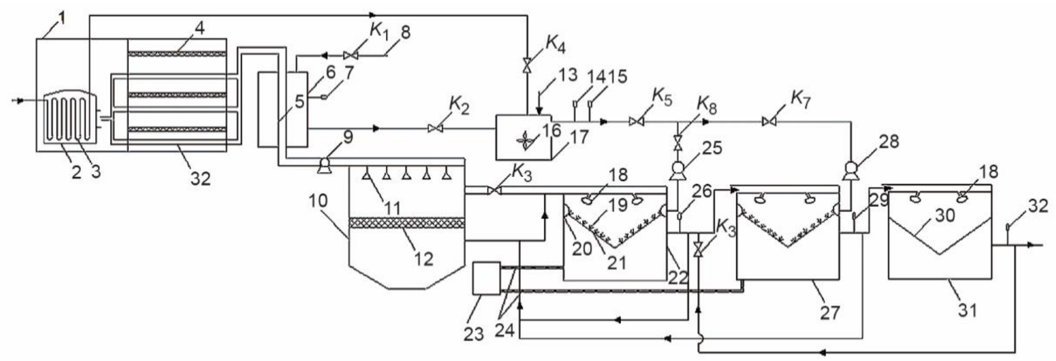

Figure 3. System diagram of flue gas waste heat recovery and desulfurization and de-nitration system;
1 – tobacco curing barn, 2 – furnace, 3 – water cooling coil, 4 – tobacco rod holder, 5 – flue gas pipe, 6 – clamping sleeve, 7 – water level monitor, 8 – water inlet, 9 – induced draft fan, 10 – air collector, 11 – horn shaped spout, 12 – filter plate, 13 – feed port, 14 – ph detector, 15 – concentration detector, 16 – agitator, 17 – mixing tank, 18 – shower nozzle, 19 – spray device, 20 – pulley, 21 – spray plate, 22 – primary filter, 23 – collection box, 24 – conveyor belt, and 25 – solution pump

Waste heat recovery occurred in coal-fired boilers and curing barn. The inner wall of the furnace in the tobacco curing barn was equipped with a water-cooled coil, which increased the external radiation heat resistance of the furnace, and recycled the radiant heat from the furnace. The flue gas near the inner wall of the furnace passed through the water-cooled coil to transfer heat to the tube. The cold water turned into high temperature water and then entered the mixing tank through the valve. The high temperature flue gas from the outlet of the furnace was divided into three channels to the flue pipe, and the heat was evenly dissipated. The hot air passed through the three-layer space in the flue house. The tobacco leaves in the upper, middle and lower sheds were heated more evenly, and the quality of the roasted tobacco leaves was improved. After evaporating and curing the water vapor of the tobacco leaves, it was led by the induced draft fan to the center of the clamping sleeve. A water level monitor was installed in the clamping sleeve. If the water level was lower than a certain value, the valve K_1 was opened to inject water from the water inlet. The flue gas pipe in the clamping sleeve was surrounded by water, which absorbed the heat of the flue gas to increase the water temperature and flowed into the mixing tank through the valve K_2. The high temperature flue gas was absorbed by the water and became low temperature flue gas. It entered the air collector along the horn-shaped nozzle, which could swing from side to side. The inlet pipe diameter was small and the outlet pipe diameter was large. The change of pipe diameter reduced the flue gas flow rate and increased the residence time of flue gas on the filter plate, then it passed through the filter plate due to gravity. The filter plate was equipped with a filter screen, and pulleys and chains were symmetrically arranged on both sides. The chain was fixed on both sides of the metal frame of the filter plate. The pulley drove the chain to move forward and backward, and then drove the filter plate to tilt back and forth at an angle of 30°. The principle was shown in fig. 4. The flue gas followed the front and back tilt of the filter plate and the swing of the horn-shaped nozzle to increase the contact area between the air and the filter which made the entrained flue gas and dust in the flue gas particles collide with the filter so that it was absorbed and filtered out more effectively. The filtered flue gas passed through the filter plate and dissolved in the water below to form waste water. The filter plate can be taken out regularly for dust cleaning.

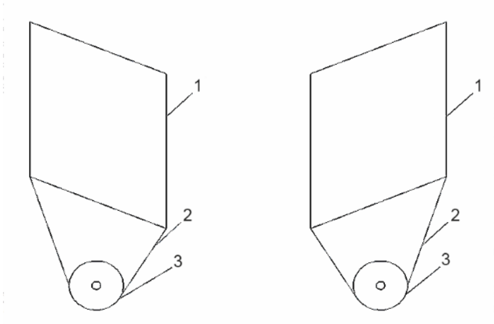

Figure 4. Front and back tilt view of filter plate; *1 – filter plate, 2 – chain, and 3 – pulley*

The medium temperature water was supplied by the mixing tank and the high temperature water by the water-cooling coil. The limestone and sodium chlorate at the feed inlet and the medium temperature water entered into the mixing tank at the same time to form a medium temperature mixed solution. A pH detector and a concentration detector were equipped at the water outlet of the mixing tank. After the mixed solution with medium temperature was uniformly stirred by the agitator to reach a certain pH value and concentration, it flowed into the primary filter, and the valves K_5 and K_6 were opened at this time. The high temperature water in the water-cooling coil flowed into the mixing tank and was fully stirred with limestone and sodium chlorate to form a high temperature mixed solution. When the valve K_6 was closed, and the valves K_5, K_7 were opened to allow water to flow into the secondary filter through the solution pump 2# by detecting the pH value and concentration.

Three-effect filter desulfurization and de-nitration device included a primary filter, a secondary filter, and a tertiary filter. The enlarged view of the three-effect filter plate with composite fiber filter material was shown in fig. 5. According to the case analysis, the filtration performance of composite filter materials was more obvious, which could save energy to the greatest extent while ensuring the quality of tobacco leaves.

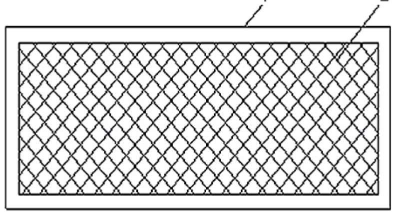

Figure 5. Three-effect enlarged view of filter plate; *1 – filter plate and 2 – filter net*

The outlet of each stage filter was equipped with a composition analyzer. If the composition analyzer at the outlet of each stage filter did not meet the standard, it will return to the previous stage filter for re-filtering. After several round-trip filtering, good desulfurization and de-nitration could be achieved. The working principle of the primary filter is given as follows: the primary filter was equipped with a shower nozzle, a V-shaped spray plate that can slide up and down through a pulley, and the spray plate was equipped with spray devices and holes. A small amount of gas in the gas collector that failed to pass the filter plate in time and the insoluble gas and the waste water in the air collector through the shower were injected into the primary filter through the valves. The medium temperature mixed solution in the mixing tank was sent to the spray device through the valves K_5, K_6 and the solution pump. The gas-liquid mixture in the shower was sprayed downward, while the medium temperature mixed solution in the spray device was sprayed upward. The movable spray plate up and down made the waste water and flue gas from the shower in the primary filter fully contact with the medium temperature mixed solution for chemical reaction. The generated solid gypsum and other products fell into the bottom of the primary filter through the holes of the spray plate, and then were transported to the collection box through the conveyor belt. At the same time, the porous structure inside the composite fiber filter material intercepted dust particles. The waste water and flue gas in the primary filter were detected by the composition analyzer, and after reaching the standard, it will enter the secondary filter for re-filtering, otherwise it will return to the primary filter for re-filtering.

The working principle of the secondary filter was the same as that of the primary filter, but the mixed solution in the spray device of the secondary filter was a high temperature mixed solution. After the flue gas passing through the primary filter entered the secondary filter, due to the increased temperature of the mixed solution, and the filter material was a composite material, the desulfurization rate and de-nitration rate were further improved compared with the primary filter. The generated solid gypsum and other products fell into the bottom of the secondary filter through the holes of the spray plate, and then were transported to the collection box through the conveyor belt. The waste water and flue gas in the secondary filter were detected by the composition analyzer, and after reaching the standard, it will enter the tertiary filter for re-filtering, otherwise it will return to the primary filter for re-filtering.

The tertiary filter was equipped with a shower nozzle and a V-shaped filter screen that can move up and down. The upper surface of the filter screen was covered with a layer of linoleum, and the lower surface was covered with active coke. The waste water and flue gas from the secondary filter enters the tertiary filter, and was sprayed on the filter screen through the shower nozzle. The linoleum can absorb the oil in the waste water and the flue gas, and at the same time block the waste water above the filter screen. The flue gas penetrated the linoleum and was stored in the microporous structure of the activated coke to achieve more thorough desulfurization and de-nitration. The waste water and flue gas in the tertiary filter were detected by the composition analyzer, and if they failed to meet the standard, they would be returned to the second-stage filter through the valve. After re-filtering, the up-to-standard flue gas was discharged into the atmosphere, and up-to-standard water was used to irrigate the tea garden.

Conclusion

The temperature of the upper and lower sheds in the conventional coal-fired smoke house was obviously higher than that of the upper shed. The temperature difference between the upper and lower sheds was 2.4-10.5 °C and the humidity difference was 2 -31.2 g/kg. The temperature and humidity of the shed were uneven, which caused the tobacco leaves in the lower shed to mature faster than the tobacco leaves in the upper shed. For every unit mass of hot air recovered, 0.762 kg of standard coal can be saved per hour, which can reduce emissions of 34.671 kg of CO_2, 0.032 kg of SO_2, and 0.005 kg of NO_x. A coal-fired flue gas waste heat recovery and three-effect filter desulfurization and de-nitration system was proposed to improve the uniformity of the overall tobacco leaf temperature and humidity, and realize the integration of waste heat recovery of coal-fired boilers and flue gas pollutants treatment. And saving energy to the greatest extent while ensuring the quality of tobacco leaves.

Acknowledgment

This work was supported by the Science and Technology Project of Changzhou City (CE20212045) of China.

References

[1] Li, S. D., *et al.*, Analysis of Color Changes of Upper Leaves of Flue-cured Tobacco K326 With Different Opening Degrees During Curing (in Chinese), *Southwest China Journal of Agricultural Sciences*, *33* (2020), 2, pp. 90-297
[2] Li, Z., *et al.*, Analysis of Dynamic Model of Color Change During Air-Curing Process of Flue-Cured Tobacco (in Chinese), *Southwest China Journal of Agricultural Sciences*, *33* (2020), 2, pp. 298-306
[3] Ding, Y. F., *et al.*, Study on Physiological Indexes and Color Value Changes of Tobacco Leaves during Curing (in Chinese), *Acta Agriculturae Jiangxi*, *33* (2021), 1, pp. 50-54
[4] Li, Y. L., *et al.*, Influence of Wet Bulb Temperature on the Curing Quality of Middle Tobacco Leaves (in Chinese), *Tianjin Agricultural Sciences*, *25* (2019), 11, pp. 4-38
[5] Zhao, S. C., *et al.*, Determination of Optimum Humidity for Air-Curing of Cigar Tobacco Leaves During the Browning Period, *Industrial Crops and Products*, *183* (2022), Sept., 114939
[6] Shi, Y. C,, *et al.*, Effects of Different Stable Times at Key Temperatures in Yellowing Stage on Quality of Tobacco Leaves after Curing (in Chinese), *Journal of Mountain Agriculture and Biology*, *37* (2018), 4, pp. 36-40
[7] Deng, X. H., *et al.*, The Dynamic Changes of Major Chemical Components of Flue-curing Tobacco Leaf in Bulk -Curing of Different Wet Bulb Temperature of Key Temperatures (in Chinese), *Chinese Agricultural Science Bulletin*, *29* (2013), 6, pp. 213-216
[8] Wang, W. W., *et al.*, Effects of Different Curing Techniques of Yellowing and Leaf-drying Stage on the Cell Wall Substances in Flue-cured Tobacco CB-1 Leaves (in Chinese), *Chinese Journal of Tropical Crops*, *37* (2016), 5, pp. 1003-1008
[9] Ye, Z. C., *et al.*, Performance Optimization and Analysis of a New Closed Heat Pump Flue-cured Tobacco System (in Chinese), *Building Energy & Environment*, *39* (2020), 5, pp. 79-83
[10] Ai, Y. F., *et al.*, Experimental Study on Temperature Fluctuation Characteristics of Air-source Heat Pump Curing Barn, *Journal of Thermal Science and Technology*, *19* (2020), 6, pp. 511-517
[11] Qiu, Z. D., *et al.*, Application of Tobacco Stem and Sawdust Formulated Biomass Fuel in Tobacco Curing (in Chinese), *Journal of Fujian Agriculture and Forestry University (Natural Science Edition)*, *50* (2021), 1, pp. 10-15
[12] Tan, F. L., *et al.*, Practical Effect of Biomass Briquette Fuel and Coal for Tobacco Curing (in Chinese), *Modern Agricultural Science and Technology*, *10* (2014), pp. 201-209
[13] Xu, H. F., *et al.*, Research on Recycling Technology of Humid Air's Waste Heat Experiment of Bulk Curing Barn's Heating System (in Chinese), *The Journal of New Industrialization*, *6* (2016), 11, pp. 81-86
[14] He, C. H., *et al.*, Controlling the Kinematics of a Spring-Pendulum System Using an Energy Harvesting Device, *Journal of Low Frequency Noise, Vibration & Active Control*, *41* (2022), 3, pp. 1234-1259
[15] He, J. H., Elazem, N. Y. A., The Carbon Nanotube-Embedded Boundary Layer Theory for Energy Harvesting, *Facta Universitatis Series: Mechanical Engineering, 20* (2022), 2, pp. 211-235
[16] Jurisevic, N. M., *et al.*, Assessment of Predictive Model for the Estimation of Heat Consumption in Kindergartens, *Thermal Science*, *26* (2022), 1, pp. 503-516
[17] He, C.-H., *et al.*, A Fractal Model for the Internal Temperature Response of a Porous Concrete, *Applied and Computational Mathematics*, *21* (2022), 1, pp. 71-77
[18] Wang, Q. L., *et al.*, Intelligent Nanomaterials for Solar Energy Harvesting: From Polar Bear Hairs to Unsmooth Nanofiber Fabrication, *Frontiers in Bioengineering and Biotechnology, 10* (2022), July, 926253
[19] He, J. H., Abd-Elazem, N. Y., Insights into Partial Slips and Temperature Jumps of a Nanofluid Flow over a Stretched or Shrinking Surface, *Energies, 14* (2021), 20, 6691

[20] He, J. H., *et al.*, Insight into the Significance of Hall Current and Joule Heating on the Dynamics of Darcy-Forchheimer Peristaltic Flow of Rabinowitsch Fluid, *Journal of Mathematics, 2021* (2021), Oct., 3638807
[21] Chen, C. L., *et al.*, Performance Analysis and Optimization of a Solar Powered Stirling Engine with Heat Transfer Considerations, *Energies, 5* (2012), 9, pp. 3573-3585
[22] Stojic, N. P., *et al.* Improving Design and Operating Parameters of the Recuperation for Waste Heat Recovery from Rotary Kilns, *Thermal Science, 26* (2022), 1, pp. 717-734
[23] Al-Yassiry, A. A., Al-Rubaye, R. T. A., A Kinetic Study of HKUST-1 for Desulfurization Application, *Thermal Science, 25* (2021), 2, pp. 1193-1202
[24] Zhao, Y. J., *et al.*, Analysis and Evaluation of the Influence of Heat Storage Material on Coke Oven Flue Gas Exothermic Process, *Thermal Science, 25* (2021), 2, pp. 1095-1108

Paper submitted: May 12, 2021
Paper revised: June 12, 2022
Paper accepted: June 15, 2022