NUMERICAL SIMULATION AND EXPERIMENTAL VERIFICATION OF STABILITY ON MULTI-CAVITY SPIRAL CASCADE HEAT TRANSFER SYSTEM

by

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In order to improve the insufficient effect of heat transfer in pyrolysis carbonization system and reveal the effects of velocity and temperature field of hot flue gas on heat transfer and stability in the biomass, the structure with rectangular groove combined with a spiral baffle is designed to form a multi-cavity spiral cascade heat transfer system. Numerical simulation and experimental verification of stability are carried on multi-cavity spiral cascade heat transfer system. The results show that the hot flue gas with high temperature flows fast at the inlet and outlet, while the flow speed is slow and stable in the cavity of heat transfer. The temperature of hot flue gas reaches the highest at the entrance, and decreases in the heat exchange chamber in a cascade. The spiral inclination angle of 35° and the pitch of 1.2 m. The combustion of gas produced by pyrolysis of raw materials can meet the requirement of continuous and stable operation, when the temperature of monitor point 1, 3, 6, and 8 reaches 800 °C, 530 °C, 250 °C, and 200 °C, respectively. The temperature of hot flue gas changes fluctuate in the range of 15 °C. The combustion of pyrolysis gas generated during the pyrolysis process of raw materials can ensure the continuous and stable operation of the equipment.

Key words: *numerical simulation, verification, stability, heat transfer, carbonization*

Introduction

There are abundant biomass resources all over the world. The biomass resources are difficult to recycle at present. Most of them will still be burned on-site as the main treatment method in most areas, which not only pollutes the environment but also wastes energy. The biomass can be converted into biochar via pyrolysis. The biochar plays an important role in many fields such as agriculture, energy, and environmental protection. Many kinds of reaction devices for biomass carbonization have been developed at home and abroad, such as up-suction fixed-bed reactor, down-suction fixed-bed reactor, circulating fluidized bed reactor, vacuum moving bed reactor, and rotating cone reactor. Nevertheless, the pyrolysis process of biomass varies with carbonization equipment. The Application of continuous biomass carbonization technology has advantages of convenient process control and stable product quality [1]. It is the

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critical point of biomass carbonization technology in the future. Moreover, another problem of carbonization equipment is insufficient effect of heat transfer. Zhao *et al.* [2] proposed a process scheme of continuous pyrolysis of biomass for carbon gas-oil co-production combining with the latest progress of biomass carbonization technology and the characteristics of agricultural and forestry residue raw materials. Cong *et al*. [3] designed the pilot system of carbon, gas and oil poly-generation based on biomass continuous pyrolysis process.

However, the effect of velocity and temperature field should be further researched. It is usually considered expensive, time-consuming and situation-specific to only use experimental methods for studying heat transfer [4]. Alternatively, numerical simulation is an effective method for research on heat exchanger performance. It is overall a cost-effective strategy for examining the velocity and temperature distributions in the process of heat transfer [5].

Chang *et al.* [6] explored the numerical simulation experiment on flow field of biomass gas. It is proved numerical simulation is an effective method to research the flow characteristics of biomass gas. Deng *et al.* [7] simulated the air-flow distribution in low profile cross ventilated dairy cattle barn by CFD simulation method. The simulation results can provide references for the optimal design of the air-flow pattern in the low profile cross ventilated cattle barn. Dong *et al.* [8] simulated the biomass gas and tar torrential flow characteristics in cyclone separator, the simulation results are in good agreement with the experimental data.

Nevertheless, the issues of the effect of velocity and temperature on multi-cavity swirling cascade heat transfer system are little examined. As stated previously, the objectives of this study are:

– To design a structure with appropriate parameters forming a multi-cavity spiral cascade heat transfer system.
– To reveal the effects of velocity and temperature field of hot flue gas on heat transfer and stability in the biomass pyrolysis carbonization system by numerical simulation method.
– To determine the appropriate heating source mode, study the rationality of the structure design and the accuracy of the numerical simulation through the stability experiment of heat transfer system.

Design of heat exchanger equipment

The equipment mainly consists of sealed uniform distribution device, continuous biomass pyrolysis carbonization device, thermal insulation cooling and the carbon discharging device. as shown in fig. 1. Pyrolysis reaction device is an important part of pyrolysis and carbonization equipment. It is a double-layer sleeve structure, also known as rotary cylinder. Its inner layer is a feeding device and the outer layer is a high temperature heat exchanger. The outer wall of the sleeve is equipped with burners and induced draft fans. The main structure is shown in fig. 2. Heat exchanger directly affects the pyrolysis effect of materials.

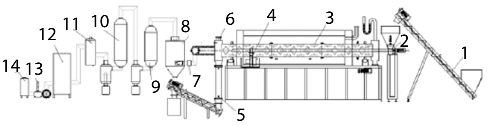

Figure 1. Overall structure of continuous pyrolysis carbonization equipment; *1 – feeding machine, 2 – screw feeder, 3 – rotary cylinder, 4 – hot air furnace, 5 – cooling carbon removal device, 6 – explosion-proof device, 7 – metal flame arrester, 8 – dust collector, 9 – primary condenser, 10 – secondary condenser, 11– electrostatic coke capture, 12 – gas scrubbing device, 13 – blower, 14 – water seal flame arrester*

The bio-char is the main product of slow pyrolysis unlike pyrolysis oil, which is the main product of fast pyrolysis. The process of pyrolysis carbonization is divided into four slow and uniform stages in order to reduce the output of pyrolysis oil and increase the output of bio-char ensuring the quality of bio-char. They are drying, pre-carbonization, carbonization and calcination. The temperature in each stage must gradually increase. Therefore, the equipment adopts counter-current heating mode, that is, the flow direction of hot flue gas is opposite to that of material. As shown in fig. 3, the material is orderly conveyed from right to left. The flow direction of high temperature hot flue gas is from left to right, and the temperature decreases gradually.

The flue chamber is divided into four parts by the rectangular structure. The upward flow of hot flue gas is blocked by the groove forming a forced subsidence state, which effectively improves the heat transfer efficiency. The multi-chamber swirl cascade heat transfer structure is formed with the combination of the groove and the spiral baffle heat exchanger [9]. The structure is shown in fig. 4.

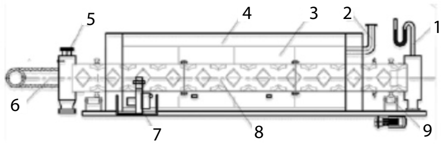

Figure 2. Schematic view of feeding system for carbonization; *1 – safety explosion-proof device, 2 – flue gas passage, 3 – multi-chamber heat exchange system, 4 – sealing insulation layer, 5 – dust removal and decoking carbon removal device, 6 – venting, 7 – burner, 8 – four-wire spiral plate copying structure, 9 – gear transmission system*

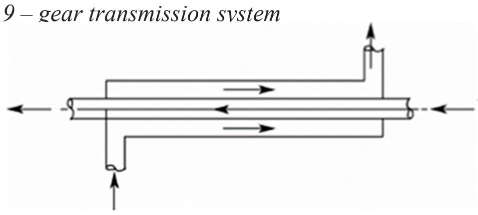

Figure 3. Flow of heat transfer system

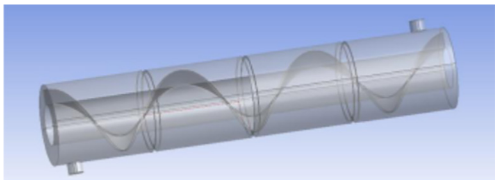

Figure 4. Schematic view of multi-cavity swirl cascade heat exchange device

Simulation experiment of heat transfer system

The specific parameters of spiral structure in the heat exchange system were determined according to the requirements of pyrolysis carbonization process through simulation tests. The flow characteristics and temperature distribution of the hot flue gas in the heat exchange system were simulated and analyzed in order to verify whether the design goal was achieved [10].

It is considered that hot flue gas is incompressible Newtonian fluid [11]. The calculation conditions and structural model are simplified as follows with the premise of ensuring quality:

– the flow and heat transfer process of hot flue gas with high temperature are stable,
– the change of density and specific heat capacity of hot flue gas in the heat transfer process are ignored,
– the hot flue gas is incompressible Newtonian fluid, continuous and isotropic,
– there is no slip boundary condition and the wall is smooth,
– the center surface is symmetrical boundary, and
– the temperature of the wall outside the tube is constant.

Eight co-ordinate points are selected as hot smoke temperature monitoring points and the numerical simulation is carried out as shown in fig. 5.

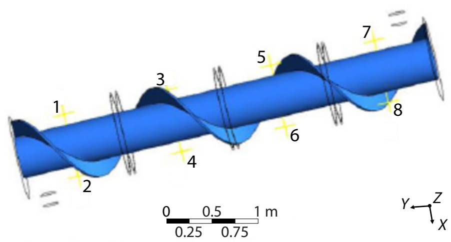

Figure 5. points location for monitoring temperature of flue gas

Determination of spiral baffles par ameters

The pyrolysis and carbonization of biomass raw materials should first go through the drying stage. According to the literature, the optimum temperature of this stage should be about 200 °C [12]. In order to ensure the quality of bio-char, the spiral baffles with different pitches were simulated when the spiral angle was 35°. The spiral structure which could make the outlet temperature of hot flue gas close to 200° was selected. As the limited length and height of heat exchanger flue chamber, if the pitch is too short, it is difficult to achieve in actual processing and the spiral blade is too dense, which is prone to fouling blockage. If the pitch is too long, the flue gas trajectory is relatively smooth and cannot achieve the anticipated effect of hindering circle round. Through consulting a large number of literatures and combining with the actual situation, the simulation tests of three structures with screw pitch of 0.8 m, 1.2 m, and 1.6 m were carried out, respectively. The results show that the outlet temperature of hot flue gas is 213 °C closest to the target temperature of 200 °C when the screw pitch is 1.2 m.

Results and discussions

Analysis of velocity field results

The hot flue gas with high temperature flows faster at the inlet and outlet, however, slowly and steadily in the heat exchange flue chamber. The geometrical degree determines the degree of streamline density. The smaller the cross-section of the fluid-flow is, the denser the streamline becomes. Therefore, the streamline is denser at the entrance and the exit, while the other parts are more dispersed.

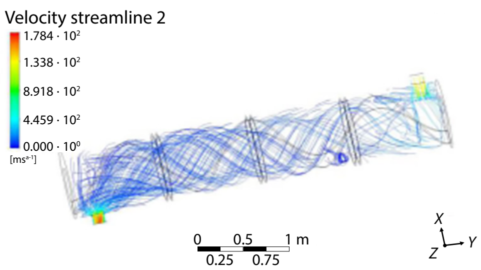

Figure 6. velocity streamline diagram of hot flue gas

The disturbance motion of flue gas-flow is increased with the effect of diversion and sectional design of the spiral baffle. The flue gas rotates periodically in the heat exchange chamber. Its flow speed reduces and retention time increases. The hot flue gas contact with the rotary cylinder better. The turbulence develops fully. the heat transfer intensity is increased. The heat transfer is more sufficient as shown in fig. 6.

Analysis of temperature field results

According to fig. 7, the temperature of hot flue gas reaches the highest at the inlet and decreases in the heat exchange chamber in a cascade. The temperature remains within the required range during the whole heat exchange process. The spiral blade represents the temperature of the fluid close to the first layer of the wall mesh, that is, the temperature of the flue gas closest to the wall surface. Due to the blocking effect of rectangular grooves, the rising of high temperature flue gas is blocked and forced to sink in the flow process, resulting in lower outer wall temperature and reducing heat transfer loss.

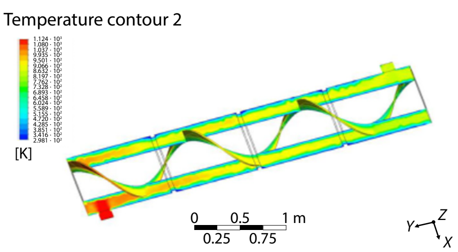

Figure 7. Figure of Section temperature

According to the numerical monitoring points of hot flue gas temperature, the simulation results are shown in tab. 1. Due to certain differences in the co-ordinate points, the temperature values of the simulation monitoring points are different from those of the test monitoring points. The trend is same conforming to the design objectives and the technical requirements of biomass pyrolysis.

Table 1. Temperature simulation value of eight co-ordinate points

Position	Furnace temperature 1	Furnace temperature 2	Furnace temperature 3	Furnace temperature 4	Furnace temperature 5	Furnace temperature 6	Furnace temperature 7	Furnace temperature 8
X-axis	–657	–657	–657	–657	–657	–657	–657	–657
Y-axis	15738	15738	14332	14332	12737	12737	11524	11524
Z-axis	176.55	–176.55	176.55	–176.55	176.55	–176.55	176.55	–176.55
Temperature	729 °C	651 °C	564 °C	587 °C	412 °C	335 °C	232 °C	213 °C

Figure 8 shows the temperature contour of the inner wall inside the smoke chamber. The wall temperature changes in stages, providing an ideal reaction environment for the pyrolysis and carbonization of biomass. The smoke chamber is divided into four parts through the rectangular groove structure. The inter-wall counter current heat transfer mode is adopted and combined with the spiral baffle structure. The multi-cavity spiral cascade heat transfer system is designed with the spiral inclination angle of 35° and the pitch of 1.2 m. The fluid dynamics simulation of the heat transfer system shows that the hot flue gas with high temperature has a rapid flow speed at the inlet and outlet, while the flow speed is slow and stable in the heat transfer flue gas chamber. The temperature of hot flue gas reaches the highest at the entrance, and decreases in the heat exchange chamber in a cascade. The temperature of hot flue gas is maintained within the required range during the whole heat exchange process.

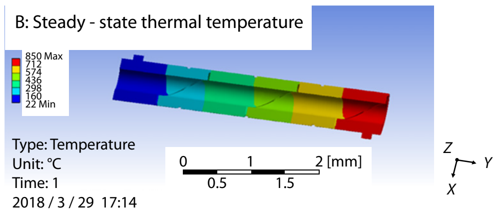

Figure 8. contour of wall temperature

Stability experiment of heat transfer system

Materials and equipment

The rice husk purchased in Daxing district (Beijing) were selected as materials of the experiment. The initial moisture content was 8.9% (W.b.). The experiment platform is a continuous rotary equipment for biomass pyrolysis carbonization. It has multi-chamber spiral cascade heat transfer structure. There are oil burner and gas burner on the lower left and roots induced draft fan on the upper right outside the rotary cylinder. The induced draft fan can control the flow rate of hot flue gas in the heat transfer system. There are eight devices to measure and control the temperature outside wall of the rotary drum. Eight values are recorded from temperature 1 to 8 according to the spiral around the order. Temperature-pressure integrated sensors monitor changes of temperature and pressure in the system in real time. These sensors are connected with the automatic control system to record the temperature and pressure values at the interval of 20 minutes.

Testing methods

When the equipment was running continuously, the temperature inside the rotary cylinder is continuously monitored. The temperature at eight monitoring points were recorded compared with the simulation results. Test as following conditions:
– Only the fuel burner provides heat source.
– The fuel burner is used for heating and pyrolysis firstly.

When the gas production reaches the standard, the heat source is converted to the gas burner. The stability of the heat exchange system and the heat supply effect of the clean recycling combustion of pyrolysis gas were tested and verified, respectively.

According to the setting of the automatic control system, the temperature values measured by eight temperature sensors within 120 minutes were taken at an interval of 20 minutes for analysis and comparison. The working condition of the fuel burner was relatively stable, the materials retention time was 40 minutes as the benchmark. The temperature condition of the test equipment within 120 minutes within continuous operation could reflect its heat transfer stability.

The fuel burner was first used for heating. When the equipment worked steadily, the newly generated pyrolysis gas entered the gas storage cabinet. When the gas storage cabinet was full, the fuel burner was replaced by the gas burner to provide the heat source for the equipment. Since the whole heat transfer process involves four stages, such as gas preheating, fuel heating, gas reuse and final extinction, the heat source is converted and the gas output and calorific value are controlled by various factors, so the test lasts for a long time, taking 50 minutes as the time interval. The total time is 450 minutes.

Results and discussion

After 25 minutes of heating with a single heat source, the equipment reached the ideal temperature and enters a continuous and stable working state. The temperature measured by eight temperature sensors in 130 minutes were taken at 20 minutes intervals. The results are shown in tab. 2. By comparing the average values of eight detection points with the simulation results, the maximum difference of temperature at monitor point 4 is 13 °C. According to the optimum temperature range of pyrolysis and carbonization mentioned previously, the difference of 13 °C is in the acceptable range. The temperature curve varies slightly in each time period, and the temperature varies in the range of 15 °C. The temperature can be maintained in the ideal temperature range for a long time and meet the technological requirements, which proves that the stable operation of the equipment can be supported by a single heat source provided by the fuel burner.

Table 2. Real-time temperature of eight monitoring points

Time [min]	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
25	722.1	645.3	565.3	582.7	409.1	337.3	243.5	230.7
55	723.4	647.9	567.7	585.1	412.3	340.9	244.7	233
75	721.1	646.9	566.4	584	412.2	340.3	242.1	232.3
95	721.5	647.6	567.2	585.4	413.5	341.4	241.5	233
115	721.6	648.7	568.3	586.3	415.3	343.6	241.4	234.2
135	722.5	649.7	569.4	586.8	417.4	345.8	241.5	235.9
155	723.7	651.3	570.5	588.1	419.1	347.3	242	237.4
Average value	721.99	645.34	553.54	574.06	422.70	342.37	238.10	238.07
Simulation value	729	651	564	587	412	335	232	213

The temperature curves of pilot carbonization equipment are divided into four periods: gas pre-heating, fuel heating, gas reuse and flameout. The furnace temperature gradually increased after a certain period of pre-heating by using the gas holder to store gas. When the gas holder pressure decreased to 0.2 MPa, the fuel heating was used for the second stage. When the heating source was replaced, the temperature decreased slightly for the short-term break-off of heating. Then the temperature increased. The temperature at monitor Point 1 reaches 800 °C gradually. The temperature at monitor Point 2 reaches 550 °C. The temperature at monitor Point 3 reaches 250 °C. The temperature at monitor Point 4 reaches 200 °C. On this condition, the carbonization production is started again and the pyrolysis gas was drained to the gas holder. The system began to run steadily in the third stage (gas reuse) until the final stage.

The temperature field oscillated only in the second stage during the whole pyrolysis and carbonization process. The temperature curve was smooth in other periods. In the second stage, the temperature field oscillated because the protection device started and extinguished automatically when the temperature of monitor Point 3 reached 630 °C. Then ignited again after the temperature drops. The system can run smoothly and continuously under these conditions.

The temperature of monitor Point 2 reaches 900 °C in the second stage. The pyrolysis gas is replaced for heating, however, the monitor Points 3-5 did not meet the conditions. Therefore, the overall furnace temperature is low. The temperature of the furnace body keeps dropping during the stage of gas reuse. The fuel must be forced to heat for secondary replacement. When the temperature of the fuel heating furnace rises, the third stage of gas reuse is re-entered. However, the calorific value of the pyrolysis gas produced in this experiment was too low to sustain the full pyrolysis reaction. The system was eventually automatically extinguished.

Comprehensive analysis shows that the temperature field of the whole rotary furnace varies in the same way. The temperature rises gradually. There is a turning point when the fuel burner is replaced, and then the temperature continues to rise. When the furnace temperature reaches 630 °C, the temperature curve begins to oscillate. The temperature curves become smoothed gradually in the stage of gas reuse until the turning point appeared in the final extinguishing stage. It is found that the gas is replace to reuse according to not only the temperature at one monitor point (800 °C) but also the temperature at each monitor point. When the temperature of monitor Points 1, 3, 6, and 8 reaches 800 °C, 530 °C, 250 °C, and 200 °C, respectively, the combustion of pyrolysis gas produced by pyrolysis of raw materials can meet the requirement of continuous and stable operation of pyrolysis system. Otherwise, flameout may occur.

When the heat source is supplied by the fuel burner alone, the temperature curve changes slightly in each period. The temperature changes fluctuate in the range of 15 °C, and can be maintained in the ideal temperature range for a long time. The temperature meets the technological requirements, which can support the stable operation of the equipment. The combustion of pyrolysis gas produced by pyrolysis of raw materials can meet the requirement of continuous and stable operation, when the temperature of monitor Points 1, 3, 6, and 8 reaches 800 °C, 530 °C, 250 °C, and 200 °C, respectively.

Conclusions

A multi-cavity spiral cascade heat transfer system is designed, which adopts the inter-wall counter current heat transfer mode and combines with the spiral baffle heat transfer structure to form a multi-cavity spiral cascade heat transfer system with the spiral inclination Angle of 35° and the pitch of 1.2 m.

Numerical simulation of the velocity and temperature of the heat transfer system shows that the hot flue gas with high temperature flows fast at the inlet and outlet, while the flow speed is slow and stable in the cavity of heat transfer. The temperature of hot flue gas reaches the highest at the entrance, and decreases in the heat exchange chamber in a cascade.

The combustion of gas produced by pyrolysis of raw materials can meet the requirement of continuous and stable operation, when the temperature of monitor Points 1, 3, 6, and 8 reaches 800 °C, 530 °C, 250 °C, and 200 °C, respectively. The temperature of hot flue gas changes in the range of 15 °C. It can be maintained in the ideal temperature range for a long time and meet the technological requirements, which proves that the stable operation of the equipment can be supported by a single heat source provided by the fuel burner. The gas is replaced to reuse according to not only the temperature at one monitor point (800 °C) but also the temperature at each monitor point. When the heat source is supplied by the fuel burner alone, the temperature curve changes slightly in each period. The appropriate heating source mode, the rationality of the structure design and the accuracy of the numerical simulation were determined through the stability experiment of heat transfer system. The control of the material residence time is accurate.

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