

Article

Experimental Study and Numerical Simulation of Gas Dryer Structure Improvement

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Abstract: The dryer is an important part of the paper drying process, and the uniformity of the dryer wall temperature distribution has an important influence on paper production quality and efficiency. In this paper, improving the temperature uniformity of the traditional gas dryer wall is taken as the research goal, and the distribution trend and uniformity of the traditional gas dryer wall temperature are studied and analyzed, and the structural improvement plan is put forward. On the basis of this, in order to further improve the uniformity of the wall temperature of the improved gas dryer, the optimization scheme of applying endothermic coating in the low-temperature area of the inner wall of the dryer is proposed. The numerical simulation and experimental research methods are used to compare and analyze the temperature uniformity of the wall of the improved gas dryer. The results show that the axial uniformity of the wall temperature of the modified gas dryer is significantly improved. Compared with the traditional gas dryer, the temperature difference of the cylinder wall is reduced from 40 °C to 13 °C, the maximum axial temperature difference of the cylinder wall is reduced by 57%, and the temperature uniformity is increased from 66.7% to 89.6%. Compared with the improved gas dryer, after the endothermic coating is applied to the low-temperature area of the inner wall of the dryer, the temperature difference of the cylinder wall is reduced from 13 °C to 7 °C, the maximum axial temperature difference of the cylinder wall is further reduced by 46%, and the temperature uniformity is increased from 89.6% to 94.4%.



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Keywords: gas dryer; structure improvement; temperature uniformity; optimization scheme

1. Introduction

The development of the paper industry is an important indicator of national modernization [1]. The dryer is an important part of the paper drying process, mainly used for the evaporation of residual excess water. The drying effect is an important indicator of paper quality, so dryers are a key issue in the paper industry [2].

Drying cylinder dryer types include steam dryers [3], multi-channel steam dryers [4], gas dryers [5], electromagnetic heating dryers [6], fuel oil/gas heating dryers [7], and microwave dryers [8], which are given priority in steam heating mode. When the paper is heated by a steam dryer, saturated steam is fed into the dryer through a steam valve. The cylinder wall is heated by condensation and heat release inside the dryer, and the heated cylinder wall dries the wet paper attached to the cylinder wall. Saturated steam condensate generated during condensation and exotherms collects at the bottom of the dryer and is difficult to discharge in time due to the relatively small coefficient of thermal conductivity of condensed water. With the continuous condensation and thickening of condensate water, the thermal resistance of steam to the cylinder wall heating will gradually increase, thus affecting the temperature uniformity of the cylinder wall. Figure 1 shows the distribution state of condensate water inside the steam dryer.

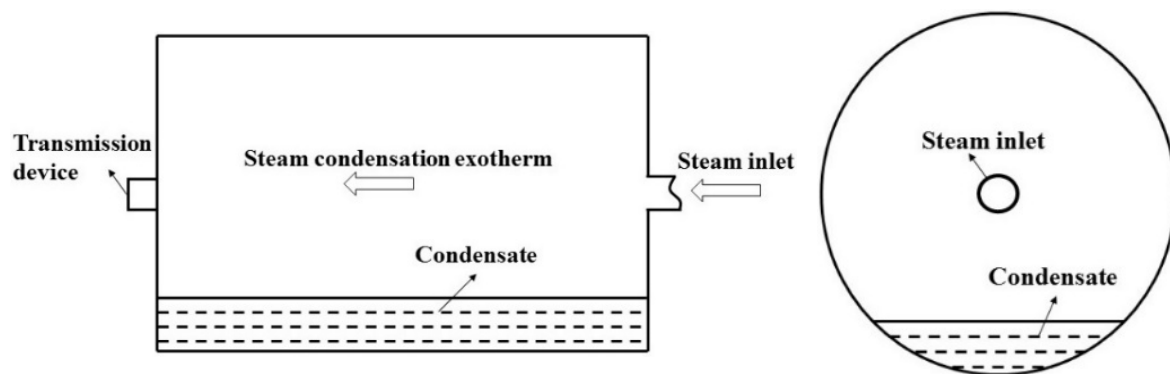


Figure 1. Distribution state of condensed water inside steam dryer.

Since the condensed water gathered at the bottom of the dryer is difficult to discharge and will seriously affect the drying quality of the paper, the researchers proposed a multi-channel steam dryer, as shown in Figure 2. The main difference between a multi-channel steam dryer and a traditional steam dryer is that in the inner wall of the steam dryer, a uniformly distributed small channel is installed in the radial direction of the dryer. The steam is transported into the dryer and enters the uniformly distributed small channel for condensation and heat release to heat the wall of the dryer. Due to the high saturated steam pressure, the condensate generated by the condensation is pushed into the condensate collection device by the steam entering afterwards, and the collected condensate is discharged out of the dryer. Steam is confined to multiple channels for condensation and heat release, which not only effectively solves the problem that it is difficult to discharge condensed water but also improves the heat exchange efficiency between steam and the wall of the dryer.

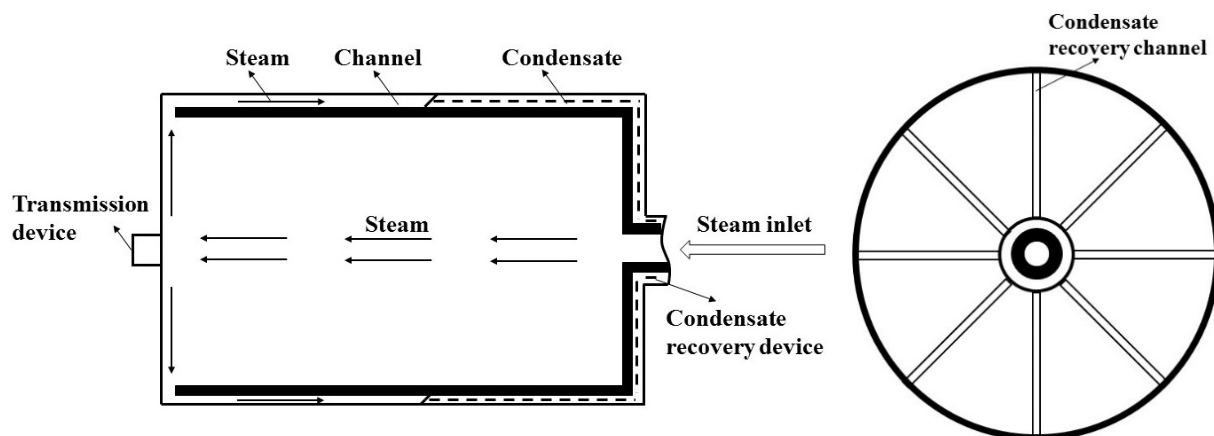


Figure 2. Multi-channel steam dryer.

The steam dryer has a simple structure and low production cost, but it has many disadvantages: (1) The wall temperature of the steam dryer is not uniform; (2) The steam pressure shall not be too high; (3) The steam temperature is difficult to control and cannot meet the requirements of different drying temperatures. The paper industry is a high energy consumption industry [9]. As the environment is deteriorating and the world's oil, coal and other non-renewable energy sources are under strict control, the traditional steam dryer will gradually be replaced by new drying technology. Electromagnetic drying and microwave drying have high energy consumption and low productivity. Natural gas is a clean energy source and has less negative impact on the environment than other traditional fuels. In order to improve the environmental pollution caused by steam dryers, many scholars have done a lot of research on gas dryers. Jiao shilong et al. [10] added an infrared radiation tube to the steam dryer to dry the paper, and the water content of the paper

decreased by 15%, thus reducing the drying cost. Bao hui et al. [11] replaced part of the steam dryer with natural gas combustion equipment, which greatly reduced the operating cost and significantly improved the environment. Liu yunfeng et al. [12] designed an oil and gas dryer to improve the influence of steam dryer pressure. Rong keqiang et al. [13] used the hot air generated by natural gas combustion to circulate heating in drying, which improved the utilization rate and economy of fuel. Xu hongxia et al. [14] proposed a new type of gas-fired horizontal paper dryer that heats the air to dry the paper. Sun jingdan et al. [15] designed and installed a gas GFDP drying test device, drying cylinder wall heating speed, and drying results that were better than those of the traditional steam dryer. Wang zhengshun et al. [16] studied the penetrating hot air drying technology, which provided a reference for the further improvement of the dryer. El Fil et al. [17–20] integrated the thermal energy storage system into the gas dryer and optimized the performance of the gas dryer through numerical simulation and experiments, reducing energy consumption by 22% and drying time by 19% compared with the traditional gas dryer. Sirimark, P et al. [21] developed a liquefied petroleum gas dryer to reduce the problem of food spoilage and studied the influence of flue gas temperature on the drying capacity of food. The results showed that the liquefied petroleum gas dryer had the lowest energy consumption and could effectively reduce the water content of food. EL-Mesery et al. [22] studied the influence of different energy sources on the drying capacity of dryers in order to solve the problems of high energy consumption and low thermal efficiency of convection hot air dryers, and the results showed that butane gas used as a drying heat source had lower energy consumption and higher efficiency. Lin, J et al. [23] studied the gas-solid coupling of an aggregate gas dryer by using the computational fluid dynamics-discrete element method (CFD-DEM) coupling method, which effectively improved the heat exchange efficiency between flue gas and aggregate. Zeng, Z et al. [24] analyzed the exergy performance, energy, and technical economy of the gas dryer, and the research results showed that the loss of high-temperature flue gas generated by gas combustion restricted the drying efficiency of the gas dryer.

At present, both steam dryers and gas dryers have the problem of uneven temperature. The large temperature difference between the cylinder walls of the dryer is easy to affect the quality of the paper, making it unable to meet the drying requirements. Therefore, in order to improve the wall temperature uniformity of the traditional gas dryer, this paper proposes a structural improvement plan for the traditional gas dryer and comprehensively uses numerical simulation and experimental research methods to compare and analyze the wall temperature uniformity of the steam dryer and the traditional gas dryer before and after the improvement.

2. Experimental Research and Numerical Simulation

2.1. Introduction to Experimental System

As shown in Figure 3a of this experimental dryer, the cylinder wall length of the dryer is 1600 mm, the diameter is 1200 mm, and the thickness of the cylinder wall is 10 mm. There are two fan-shaped flue gas outlets on the side wall of the dryer, and the flue gas outlet area is 770 mm². The combustion tubes in the dryer are shown in Figure 3b, the length of each combustion tube is 1350 mm. The wall of the combustion tube is provided with gas nozzle evenly distributed along the axial direction. The length of the gas nozzle is 32 mm, and the aperture is 1.3 mm. The nozzle is covered with a layer of metal fiber for flame equalization, the thickness of 2 mm. The gas emitted from the nozzle combines with oxygen to form a flame, which is continuously burned outside the nozzle installed on the wall of the combustion tube, where is the combustion area.

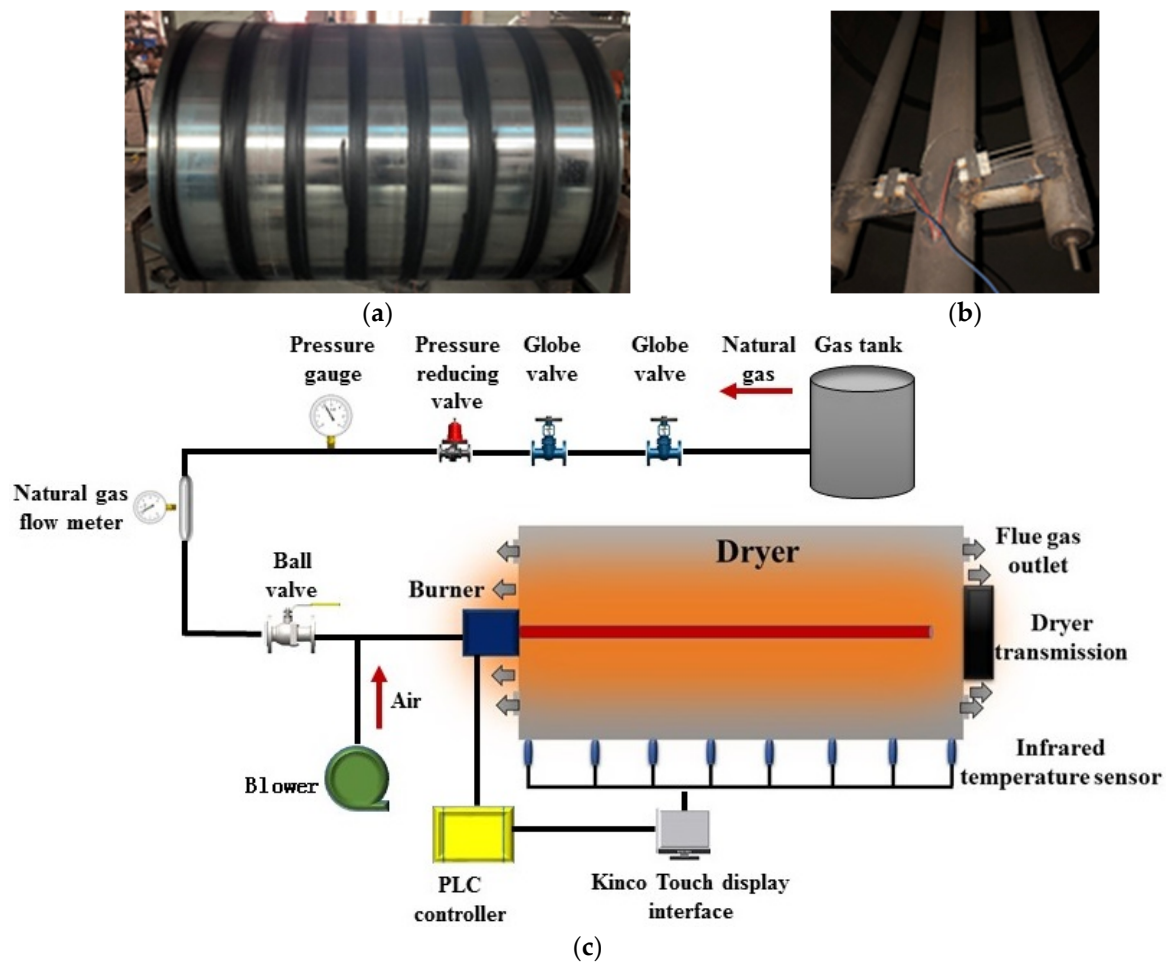


Figure 3. Main experimental equipment: (a) dryer; (b) combustion tube; (c) schematic diagram of experimental test system.

After the fan blows out the residual gas inside the dryer, the natural gas and air are premixed by the burner and then injected into the combustion tube, and then the ignition is started. The control system receives the temperature change through the infrared temperature sensor, and then supplies the gas proportional regulator accordingly. The sensor signal controls the surface temperature of the dryer to keep it within the set temperature range, so that the temperature tends to be stable. The transmission device controls the rotation speed of the dryer to meet different paper drying requirements. The control electric box detects the flashback or flameout of the combustion tube through a flame detector, and automatically controls the gas switch to prevent gas leakage. The schematic diagram of the experimental test system is shown in Figure 3c.

2.2. Measuring Instruments and Methods

2.2.1. Measuring Instrument

This experiment adopts the PLC control system of the SIEMENS series and the A/V series short and small non-contact infrared temperature sensors to monitor the temperature. This type of infrared temperature sensor integrates the sensor, optical system and electronic circuit into the stainless steel shell. The surface temperature of an object can be calculated by measuring the intensity of infrared radiation emitted by the object without touching the target. Non-contact temperature measurement is the biggest advantage of this type of infrared temperature sensor, which can easily measure targets that are difficult to reach or move. The temperature measurement range is 0~800 °C, the temperature measurement accuracy is $\pm 1\%$ or $\pm 1.5\%$ of the measured value, and the repetition accuracy is $\pm 1\%$.

or ± 1 °C of the measured value. The distribution diagram of temperature monitoring points is shown in Figure 4a. The surface of the dryer is divided into 8 zones with a spacing of 200 mm. Along the dividing line, the surface of the dryer is coated with black, high-temperature-resistant paint and polished smoothly to reduce the experimental measurement error. Eight infrared temperature sensors were installed 50 mm away from the paint to monitor and record the surface temperature of the cylinder wall, as shown in Figure 4b.

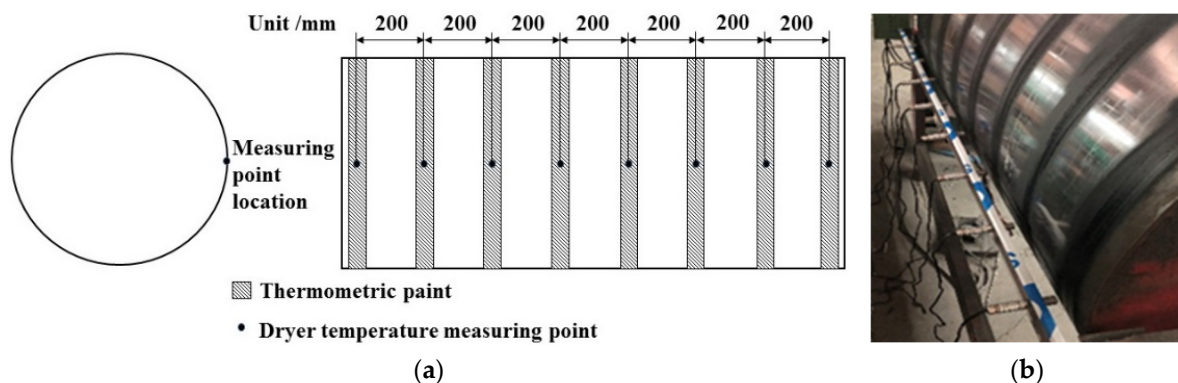


Figure 4. Temperature monitoring point distribution map: (a) location of temperature measuring point; (b) installation location of temperature sensor.

2.2.2. Measuring Steps

Step 1: keep the environment ventilated normally before the experiment, check whether the gas leaks, and check whether the instruments and meters are working normally. Step 2: wait for the fan to sweep the inside of the dryer to keep the internal environment of the dryer normal. Step 3: turn the burner on, adjust it to 45 KW, keep the power working, and wait for the temperature to stabilize. Start to record the temperature data and import it to the computer to save it. Step 4: after the above measurement is completed, close the instrument and complete the experimental measurement. Step 5: analyze and study the saved experimental data.

2.3. Numerical Simulation

2.3.1. Physical Model

The structure of the gas dryer is shown in Figure 5. The wall length of the dryer cylinder is 1600 mm, the diameter of the side wall is 1200 mm, and the wall thickness of the cylinder is 10 mm. The side of the gas dryer has two symmetrical fan flue gas outlets, each flue gas outlet area is 770 mm², the length of the combustion tube is 1350 mm.

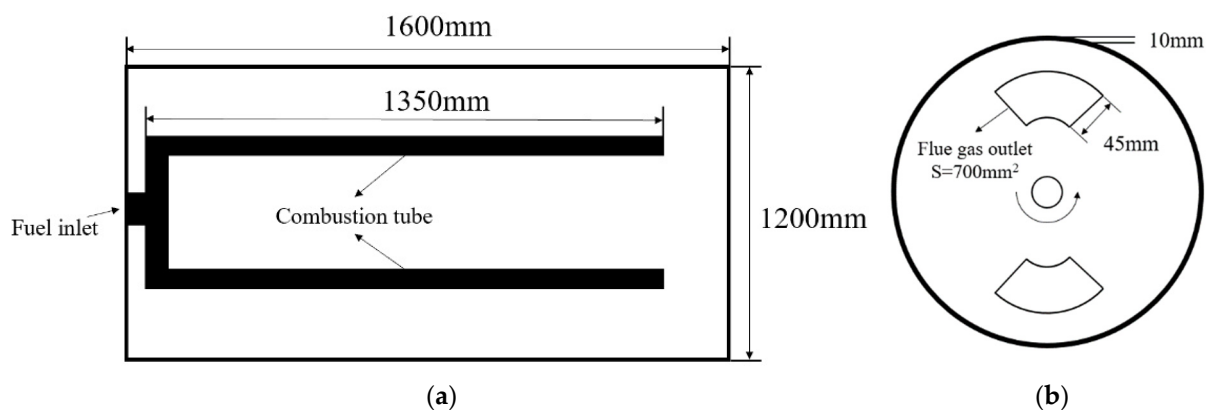


Figure 5. Gas dryer structure: (a) gas dryer structure dimensions; (b) side structure dimensions.

The structure of the steam dryer is shown in Figure 6. The wall length of the dryer cylinder is 1600 mm, the side wall diameter is 1200 mm, and the wall thickness of the dryer cylinder is 10 mm. The steam channels inside the steam dryer are evenly distributed and arranged, and the size of the channels is the same. The length of the single channel is 1580 mm, the width is 5 mm, and the height is 10 mm.

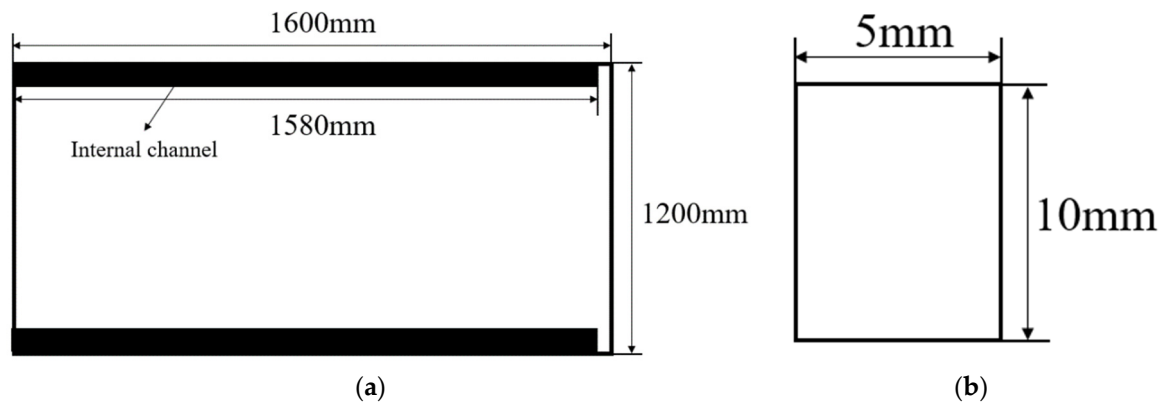


Figure 6. Steam dryer structure: (a) Steam dryer structure dimensions; (b) Channel section structural dimensions.

2.3.2. Mathematical Models and Basic Equations

The numerical model was established using ANSYS Workbench 17.2, and numerical simulations were performed on steam and gas dryers. The continuity equation, momentum equation, and energy equation must be satisfied in the numerical simulation of gas dryer and steam dryer. The basic governing equations are shown as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = S_m \quad (1)$$

Momentum equation:

$$\frac{\partial \rho}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \quad (2)$$

Energy equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot \left[u \left(\rho \vec{E} + p \right) \right] = \nabla \cdot \left[k_{eff} \nabla T - \sum_j h_j J_j + \left(\tau_{eff} \cdot \vec{u} \right) \right] + S_h \quad (3)$$

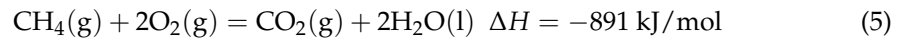
In the equation, E is the total energy of the fluid microclusters, J/kg; k_{eff} is the effective thermal conductivity, W/(m·K); h_j is the enthalpy value of component j , J/kg; J_j is the enthalpy diffusion flux of component j ; S_h is the heat of chemical reaction and other heat source terms.

The combustion process inside the gas dryer is the non-premixed combustion of natural gas and air, and the chemical substances in the combustion reaction meet the conservation equation of components [25]:

$$\frac{\partial(\rho Y_i)}{\partial t} + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i \quad (4)$$

In the equation, Y_i is the mass fraction of component i ; $\vec{J}_i$ is the diffusion flux of component i ; R_i is the net production rate of chemical reaction. S_i is the extra generation rate caused by discrete phase and source term.

Combustion chemical reaction equation [26]:



In the equation, ΔH is the reaction enthalpy when CH_4 and O_2 are completely burned; g for gas and l for liquid.

Component equation:

$$\frac{\partial}{\partial x_i}(\rho u_i c_s) = \frac{\partial}{\partial x_i} \left(\rho D \frac{\partial c_s}{\partial x_i} \right) + S_s \quad (6)$$

In the equation, c_s is the volume concentration of component s ; D is the diffusion coefficient of components; S_s is the productivity of component s .

The interior of the gas dryer is mainly heated by high-temperature flue gas in the cylinder wall. Considering the geometry of the gas dryer, the radiation characteristics and accuracy between the high-temperature gas and the wall, as well as the discrete-ordinate DO radiation model. DO radiation heat transfer equation [26]:

$$\frac{dI(\vec{r}, \vec{s})}{ds} + (a + \sigma_s)I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \Phi(\vec{s}, \vec{s}') d\Omega \quad (7)$$

In the equation, s is the length of radiation travel; $\vec{s}$ is the scattering direction; $\vec{r}$ is the position vector; a is the absorption coefficient; n is the refraction coefficient; σ_s is the scattering coefficient; σ is Stephen Boltzmann's constant; I is the radiation intensity; T is the temperature at that time; Φ is the phase function; Ω is a solid angle of space;

In the process of condensing heat transfer between the steam inside the steam dryer and the channel heat exchange surface in the multi-channel interior, the steam condensation heat transfer model needs to be added [27]:

$$\text{Quality source item: } S_m = - \left(\frac{\rho D}{1 - \omega_V} \right) \frac{\partial \omega_V}{\partial n} |_i \quad (8)$$

$$\text{Dynamic energy item: } S_{\rho V} = S_m \omega \quad (9)$$

$$\text{Energy source item: } S_h = S_m \dot{h} \quad (10)$$

In the equation, S_m is the mass flux of steam in the channel; n is the normal distance of the channel condensation heat transfer surface; $\dot{h}$ is the enthalpy flow in the process of steam condensation and heat release.

The high-temperature flue gas inside the gas dryer and the steam inside the steam dryer both belong to turbulent flow, which satisfies the dynamic law of continuous medium and has the characteristics of high Reynolds number and sufficient turbulence. The turbulence model selected is the Standard K- ϵ model [28], and the K- ϵ equation is as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (11)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \quad (12)$$

In the equation, G_k is the turbulent kinetic energy caused by the average velocity gradient; G_b is turbulent kinetic energy generated by buoyancy; Y_M contributes to pulsation expansion in compressible turbulence; S_k , S_ϵ is a custom source item; $C_{1\epsilon}$, $C_{2\epsilon}$, $C_{3\epsilon}$ are constants, $C_{1\epsilon} = 1.44$, $C_{2\epsilon} = 1.92$, $C_{3\epsilon} = 0.09$.

2.3.3. Numerical Computation Condition

The boundary conditions of the gas dryer are set as follows: the mixed gas is the mass flow inlet, and the fuel inlet flow and temperature are $21.69 \text{ m}^3/\text{h}$ and 300 K , respectively. The air-fuel ratio is 1:2; the flue gas outlet is set as pressure-outlet; the dryer keeps rotating at a constant speed, and the rotating speed is set to 1.5 rad/s . The outer cylinder wall of the dryer is made of nickel-plated material, and its emissivity is 0.11. The high-temperature flue gas and the dryer wall are radiated for heat transfer, and the fluid–structure coupling boundary condition is set between the dryer wall and the high-temperature flue gas. Convection heat transfer and radiation heat transfer were carried out between the side wall of the dryer and the external environment. The side wall of the dryer was set as a mixed boundary condition, and the natural convection heat transfer coefficients were all $10 \text{ W/m}^2 \cdot \text{K}$. The physical model is divided into unstructured grids. After grid independence verification, the total number of grids is about 4 million.

The channels in the multi-channel steam dryer are evenly distributed, so a single channel is taken as the research object to analyze the heat transfer between a single channel and the wall surface of the dryer and the uniformity of the wall temperature. Figure 7 shows a single channel model. The dimensions of a single channel are: 1580 mm in length, 10 mm in width, 5 mm in height. The boundary conditions of the steam dryer are set as follows: The channel inlet is the pressure-inlet, and the channel outlet is the pressure-outlet; the upper wall of the passage is the heat exchange surface with the wall of the dryer cylinder, and the walls on both sides of the passage and the lower surface are the adiabatic surface, which is set as the fixed wall boundary condition. The medium in the inner region of the channel is water vapor and liquid water, so it is set as the computational fluid region. The physical model of a single channel is divided by an unstructured mesh. After the independence of the mesh is verified, the total number of meshes is approximately 79,000.

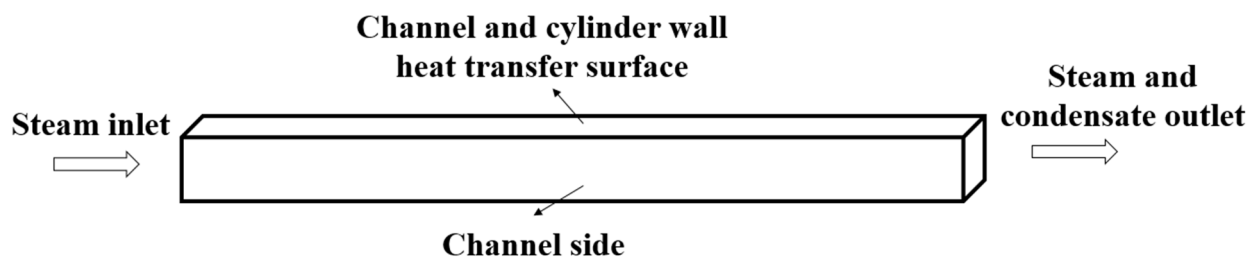


Figure 7. Single channel model.

SIMPLE algorithm is used in the numerical simulation process. In the iterative calculation process, when the residual value of the continuity equation and the momentum equation are both less than 10^{-6} and the residual value of the energy equation is less than 10^{-8} , the calculation is judged to be convergent.

3. Results and Discussion

3.1. Comparison of Temperature between Steam Dryer and Gas Dryer before Improvement

Through the above experimental measurement and numerical simulation calculation, Figure 8 shows the comparison of the temperature distribution of the traditional gas dryer. It can be seen from Figure 8 that the experimental measurements are in good agreement with the numerical calculation results, but there are still deviations due to the following simplification in the numerical simulation calculation process: In the experimental measurement process of a traditional gas dryer, an ignition device needs to be set for the combustion of gas on the outer wall of the combustion tube. The installation position of the ignition device is about 250 mm away from the intake end of the combustion tube, and there is no gas combustion around this area. However, the combustion state around the ignition device is reasonably simplified in the numerical simulation, and the outer wall of the combustion tube is set as the combustion area. Table 1 shows the temperature error table of the experimental measurement and numerical simulation of the traditional gas

dryer. It can be seen from Table 1 that the experimental measurement temperature of the traditional fuel dryer is basically consistent with the numerical simulation temperature, with a maximum error of 6.8%. Therefore, the numerical simulation model can accurately calculate the temperature and change trend of the dryer wall, and the numerical simulation method has practical significance and can meet the research needs of this paper.

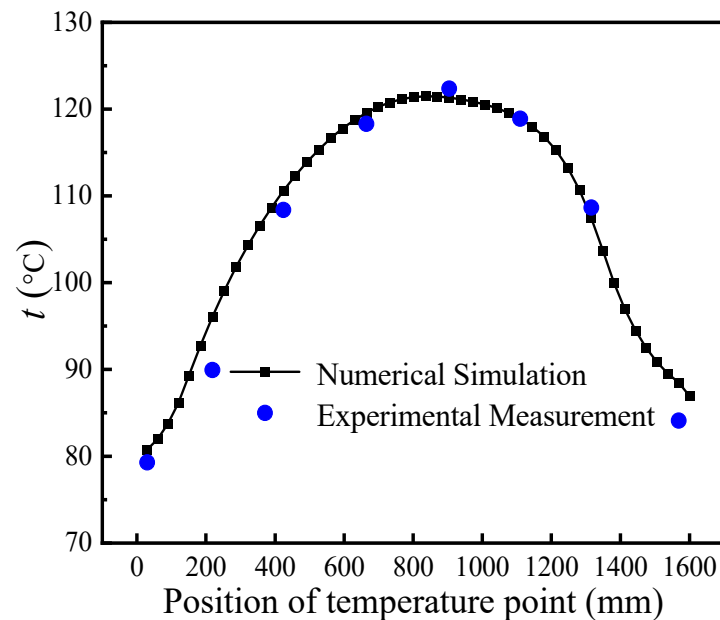


Figure 8. Comparison of temperature distribution of traditional gas dryer.

Table 1. Temperature error table of experimental measurement and numerical simulation of the traditional gas dryer.

Temperature Measuring Point (mm)	Experimental Measurement Temperature (°C)	Numerical Simulation Temperature (°C)	Temperature Error (%)
50	79.28	80.79	1.9
250	89.94	96.08	6.8
450	108.39	110.59	2.02
650	118.31	119.58	1.07
850	122.36	121.33	0.84
1150	118.89	118.73	0.13
1350	108.65	107.44	1.1
1550	84.11	88.49	5.2

The uniformity of the wall temperature of a steam dryer is analyzed by numerical simulation, and the temperature distribution is compared with that of a traditional gas dryer. Definition of wall temperature uniformity: Under the given test conditions, after stable operation of the dryer, by measuring the temperature value of the dryer wall along the axial direction at different points, record and evaluate the uniformity of the dryer wall temperature distribution. In order to better describe and calculate the temperature uniformity of the dryer wall, “Temperature Evenness” is introduced, which is the ratio between the difference between the maximum and minimum values of the measured temperature of the dryer wall and the maximum value. The higher the temperature evenness and the smaller the temperature difference, the better the temperature uniformity of the dryer wall. On the contrary, the lower the temperature evenness, the larger the

temperature difference value, which indicates that the temperature uniformity of the dryer wall is worse. Figure 9 shows the comparison of the simulated temperature distribution between a steam dryer and a traditional gas dryer. As can be seen from Figure 9, the wall temperature of the steam dryer cylinder shows a decreasing trend, and the temperature difference of the cylinder wall is 10 °C. When the steam dryer is in the radial position of 0~200 mm, the steam just enters the channel and begins to condense and release heat to heat the cylinder wall, so the temperature at this position drops rapidly. At the radial position of 200~1600 mm, the medium inside the channel is a mixture of steam and condensate water, and the temperature drop in this section begins to slow down, so the wall temperature of the steam dryer shows a gradual decrease and tends to be stable. The temperature difference of the cylinder wall of the traditional gas dryer is 40 °C. Because the high-temperature flue gas gathers in the middle of the interior, the high-temperature flue gas at both ends loses too much and the heat transfer on the wall is less, resulting in the wall temperature of the traditional gas dryer showing a parabolic state: the temperature in the middle is high, and the temperature at both ends is low.

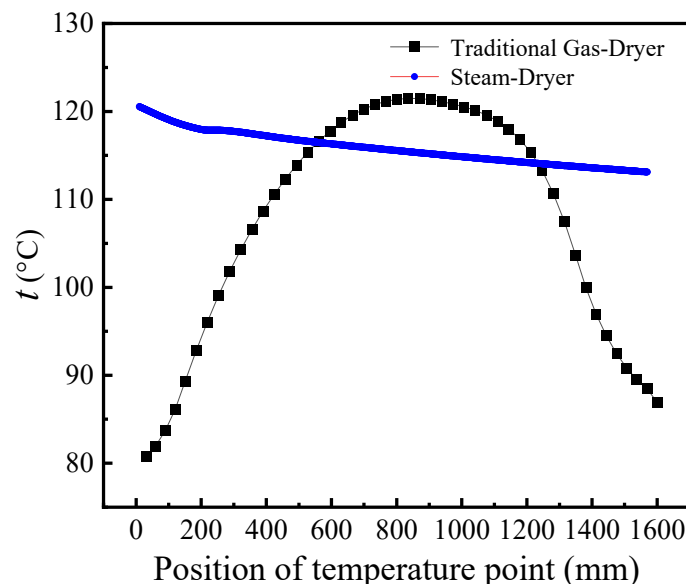


Figure 9. Comparison of simulated temperature distribution between steam dryer and traditional gas dryer.

Although the steam dryer and the traditional gas dryer both have the problem of uneven temperature, the temperature evenness of the steam dryer is 91.7% and that of the traditional gas dryer is 66.7%. The wall temperature uniformity of the steam dryer is obviously better than that of the traditional gas dryer. For the steam dryer, after the steam enters the channel, the heat is exchanged with the wall surface by condensing and releasing heat. When the steam flows along the channel to the outlet end, the steam generates condensate while condensing and releasing heat, and the temperature is constantly decreasing. Figure 10 shows the condensation heat release and zone temperature diagram of the channel. The condensation heat transfer process between steam and the dryer cylinder wall can be divided into “three temperature zones”: the saturated steam at the steam inlet continues to enter, showing gaseous distribution, so the temperature in the front section of the passage is higher, and this area is a high temperature zone. As steam continues to condense and release heat to generate condensate water, the temperature decreases continuously. The middle section of the channel is distributed in a mixed state of steam and condensate water, so the temperature in the middle section of the channel is maintained at medium. As steam continues to rush to the outlet end, condensate water increases at the end of the channel and gathers at the outlet end, which is distributed in the state of

condensate water. The temperature of condensate water is lower than that of steam, so the temperature at the back of the channel is lower, and this area is a low-temperature area.

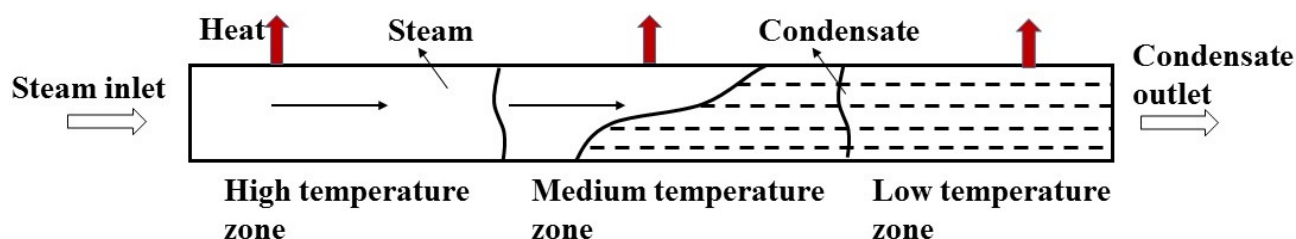


Figure 10. Condensation heat release and zone temperature diagram of channel.

There are several reasons why the wall temperature difference in a traditional gas dryer is too large: (1) The two combustion tubes are affected by the environment and structure, which leads to different gas distribution amounts and different combustion states; (2) The pressure of high-temperature flue gas generated by combustion inside the dryer is too large. Under high pressure, the flue gas flows out from both ends of the dryer too fast, and the high-temperature flue gas gathers in the middle of the dryer, resulting in high temperatures in the middle of the dryer and low temperatures at both ends, so the temperature distribution on the cylinder wall is uneven; (3) The area of the flue gas outlet is too large, resulting in less high-temperature flue gas content at both ends and small heat exchange between the flue gas and the positions at both ends of the cylinder wall.

According to the above analysis, compared with the steam dryer, the wall temperature difference of the traditional gas dryer is too large to meet the drying requirements. Therefore, it is particularly important to improve the wall temperature uniformity of the traditional gas dryer. It is necessary to propose a structural optimization and improvement plan for the existing gas dryer to improve the wall temperature uniformity of the traditional gas dryer.

3.2. Optimize the Improvement Scheme and the Temperature Distribution of the Improved Gas Dryer

In view of the unreasonable structural design of the traditional gas dryer, structural optimization and improvement were carried out on the basis of the existing gas dryer. The comparison of schematic diagrams of gas dryer structure optimization is shown in Figure 11. The structural improvement includes the following aspects: (1) The two combustion tubes inside the dryer were changed into one combustion tube without changing the combustion area of the combustion tube, so as to avoid uneven gas distribution; (2) Change the symmetrical distribution of two fan-shaped flue gas outlets into six uniformly distributed circular flue gas outlets without changing the area of the flue gas outlets; and (3) install the circular flue gas baffle at the flue gas outlet, which is made of stainless steel. Under normal conditions, the surface roughness of the stainless steel flue gas baffle is between 1.6~3.2 μm . After fine mirror polishing, the surface roughness is reduced and controlled between 0.1~0.2 μm , so that the surface is smooth, flat, and has a mirror effect, which effectively enhances the infrared radiation reflectivity of the flue gas baffle and reduces diffuse reflection. The infrared radiation reflectivity is higher than 0.8, so as to improve the internal temperature of the dryer. After the improvement, the dryer wall length, side wall diameter, cylinder wall thickness, combustion tube length, and area remain unchanged. Six uniformly distributed circular flue gas outlet structures have the same size, with a diameter of about 13 mm and an area of about 130 mm². The diameter of the flue gas baffle is 1100 mm. The physical model of the improved gas dryer was established, and meshing was completed to ensure that the numerical calculation conditions, such as the governing equation and boundary conditions, were unchanged, and the numerical simulation and experimental measurement were carried out.

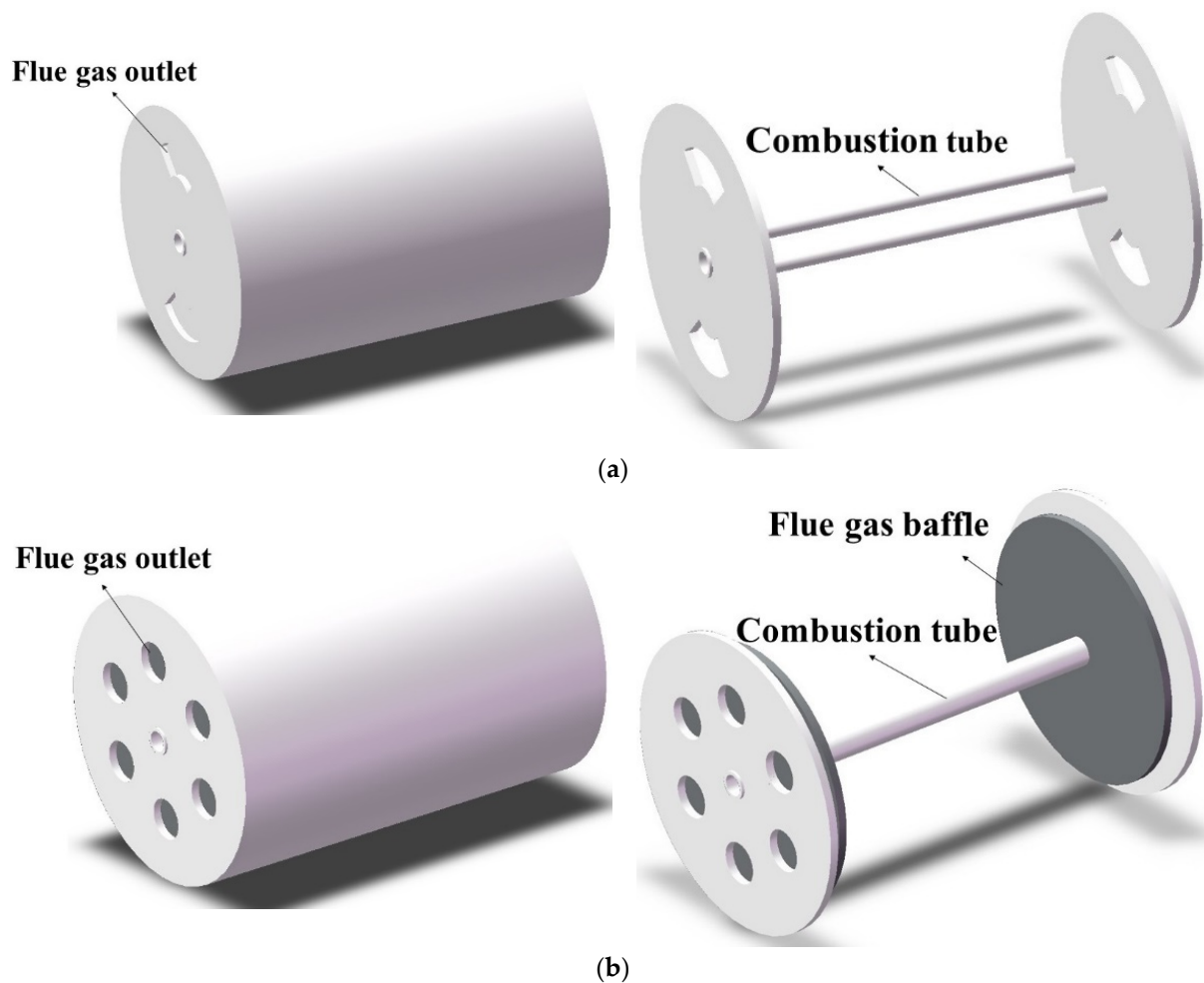


Figure 11. Comparison of schematic diagram of gas dryer structure optimization: (a) Before improvement; (b) After improvement.

Figure 12 shows the comparison of the simulated temperature distribution of the improved gas dryer. It can be seen in Figure 12 that the wall temperature uniformity of the improved gas dryer is basically the same as that of the steam dryer, and the temperature difference is reduced from 40 °C to 15 °C compared with the traditional gas dryer before the improvement. The temperature evenness increased from 66.7% to 87.5%. The comparison of the internal temperature field at a drier's section along its axis is shown in Figure 13. It can be seen from Figure 13 that after the improvement, the distribution of high-temperature flue gas inside the gas dryer is more uniform, and there is no difference in smoke content between the two ends and the middle. Due to the installation of a polished flue gas baffle at the outlet position, the flue gas can be reduced from the outlet too fast due to high pressure, and the wall temperature of the dryer can be increased. Because the flue gas outlet area is reduced and evenly distributed, the discharge flow of flue gas is reduced, the heat exchange time between flue gas and the cylinder wall is increased, and the heat exchange efficiency is improved. Therefore, based on theoretical analysis, it can be inferred that the wall temperature uniformity of the improved gas dryer will be improved.

Based on the above analysis, the structure of the existing gas dryer is optimized and improved, and the remaining parts are the same as the original ones. The real object of the improved gas dryer is shown in Figure 14. The same experimental measurement was carried out on the improved gas dryer. Figure 15 shows the comparison of the temperature distribution of the improved gas dryer. It can be seen from Figure 15 that the temperature difference of the wall of the improved gas dryer is 13 °C, which is 57% less than that of the

traditional gas dryer. The temperature evenness has increased from 66.7% to 89.6%, and its wall temperature uniformity is basically the same as that of the steam dryer.

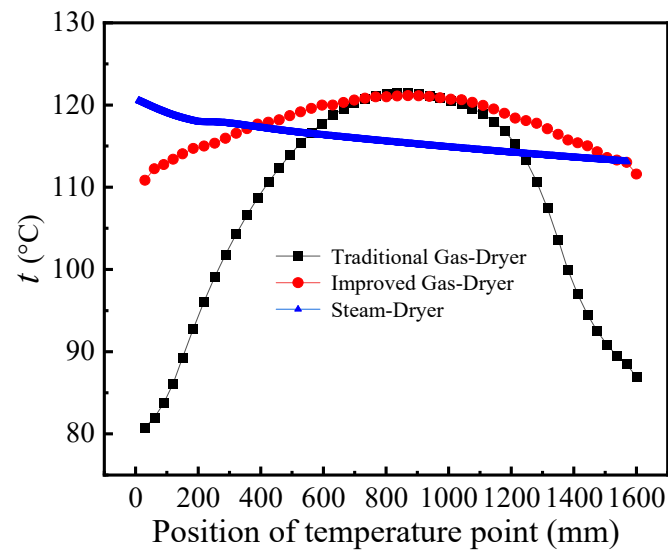


Figure 12. Comparison of simulated temperature distribution of improved gas dryer.

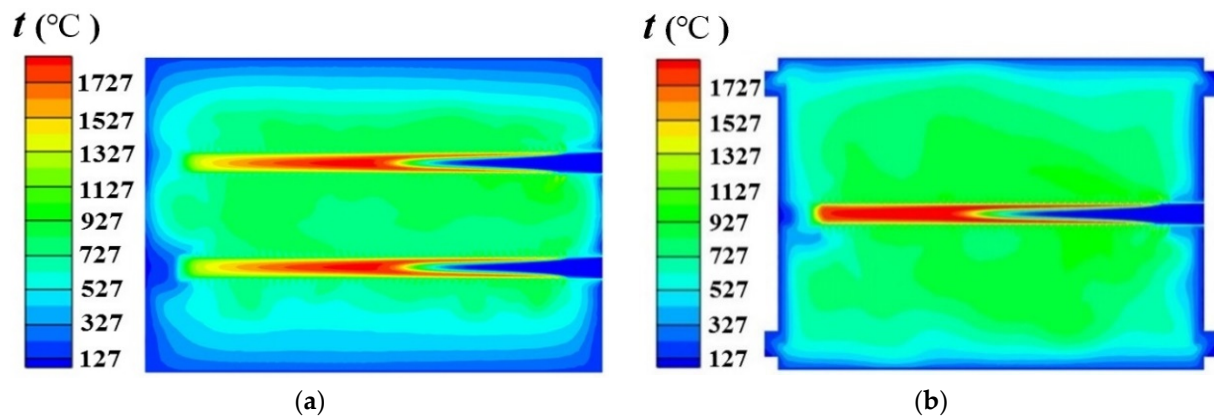


Figure 13. Comparison of internal temperature field at a drier's section along its axis: (a) Before improvement; (b) After improvement.

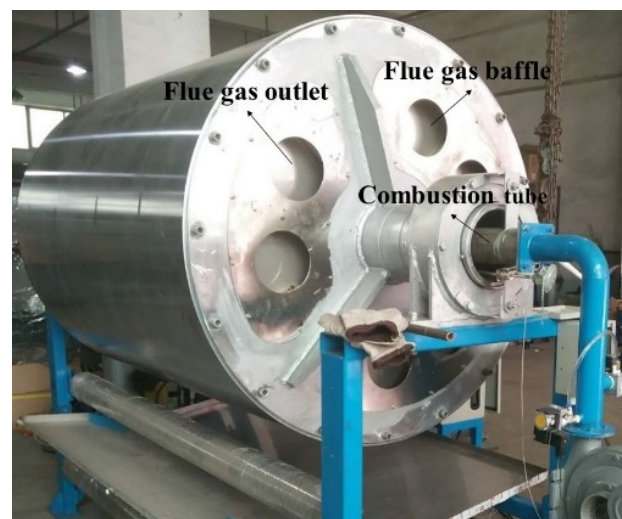


Figure 14. Improved gas dryer.

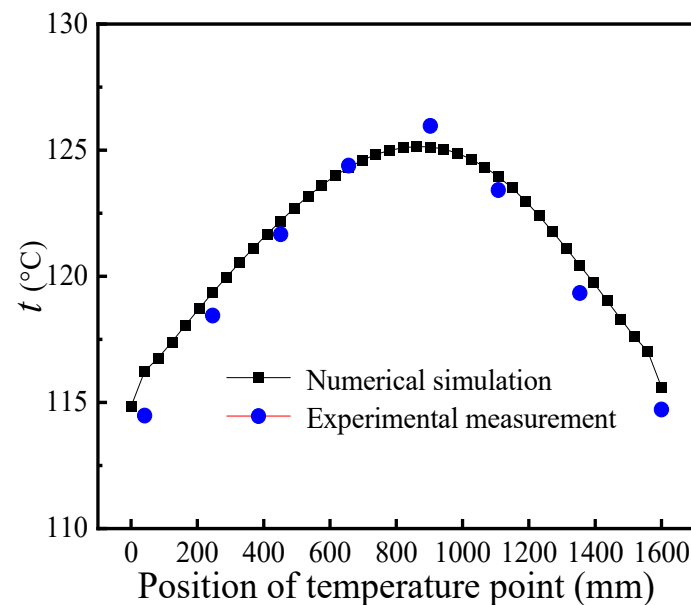


Figure 15. Comparison of temperature distribution of improved gas dryer.

3.3. Research on the Influence of Coating Optimization Scheme on the Temperature Distribution of Improved Gas Dryer

Numerical simulation and experimental measurement are carried out for the above optimization scheme, and the results show that the optimization scheme can effectively improve the wall temperature uniformity of the gas dryer. In order to further improve the uniformity of the wall temperature of the improved gas dryer wall, an optimization scheme of endothermic coating on the inner wall of the dryer is proposed, and its feasibility is verified by numerical simulation.

Although the uniformity of the wall temperature of the improved gas dryer is obviously improved and basically the same as that of the steam dryer, the wall temperature of the gas dryer still presents a distribution trend of high temperature in the middle and low temperature at both ends. Now, taking the absorption rate of the wall material of the dryer cylinder as the standard, brush the endothermic coating on the inner wall (0~400 mm, 1200~1600 mm) with a low temperature at both ends of the dryer. Increasing the blackness of the wall at both ends increases the heat absorption rate, thus reducing the temperature difference between the two ends and the middle position and further improving the wall temperature uniformity of the dryer. The physical model of a gas dryer with an endothermic coating is shown in Figure 16. The heat-absorbing coating is the wave-absorbing heat-increasing coating [29]. The coating width is 400 mm, the thickness is 1.5 mm, and the coating boundary conditions are set as follows: the coating emissivity is 0.2, the electromagnetic wave absorption rate is 90%, the thermal conductivity is 25 W/m·K, the density is 1.6 kg/m³, and the roughness is 10 µm. The physical model and mesh division of the dryer for brushing endothermic coating were completed to ensure that the parameters of the control equation and other boundary conditions were set unchanged, and the numerical simulation was performed. Figure 17 shows the comparison of the simulated temperature distribution in the dryer with endothermic coating.

It can be seen in Figure 17 that under the same working condition, when the endothermic coating is applied to the lower temperature at both ends of the dryer inner wall, the temperature increases significantly, and the wall temperature uniformity of the dryer wall is further improved. Compared with the steam dryer and the improved gas dryer, the wall temperature difference decreased from 13 °C to 7 °C, the temperature evenness increased from 89.6% to 94.4%, and the temperature difference between the cylinder walls was further reduced by 46%. The reasons for the reduction of temperature difference are as follows: (1) The endothermic coating can guide and attract electromagnetic waves within the brush-

ing range, which can reduce the reflection, refraction and scattering of electromagnetic waves in the brushing area on the wall of the dryer and can also forcibly balance the absorption of electromagnetic waves in the high temperature area in the middle of the gas dryer. (2) The endothermic coating has low reflectivity of the incoming electromagnetic waves, and the endothermic coating has good broadband absorption. (3) After the electromagnetic wave enters the coating, a part directly penetrates through the coating to reach the wall of the dryer. Part of the electromagnetic wave energy is converted into heat energy through the quality loss of the coating, and then the heat energy is transferred to the wall of the dryer through the conduction or radiation of the coating. The endothermic coating utilizes the characteristics of electromagnetic waves, one of which is to increase the absorption and utilization of electromagnetic waves in the brushing area of the dryer wall. The other is to control the radiated electromagnetic waves in the brushing area of the dryer wall. The internal temperature field at a drier's section along its axis with endothermic coating is shown in Figure 18. It can be seen from Figure 18 that when the temperature of the dryer wall is stable, the heat absorption rate at both ends of the dryer with the endothermic coating is significantly increased, and the slight temperature increase is basically the same as that at the middle position. Therefore, based on the numerical simulation results of the coating optimization scheme, it can be inferred theoretically that the scheme can further improve the wall temperature uniformity of the gas dryer.

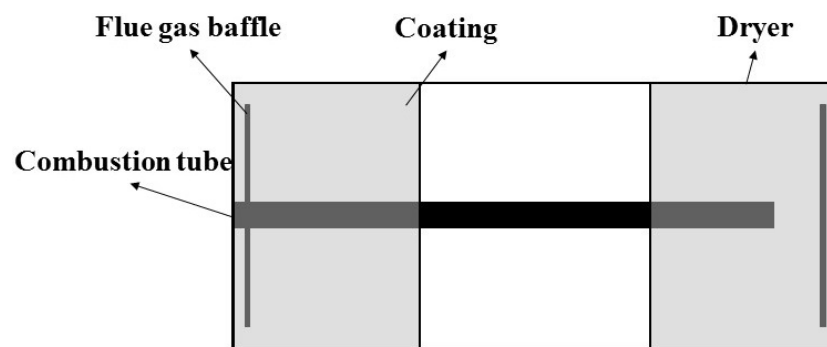


Figure 16. Physical model of gas dryer with endothermic coating.

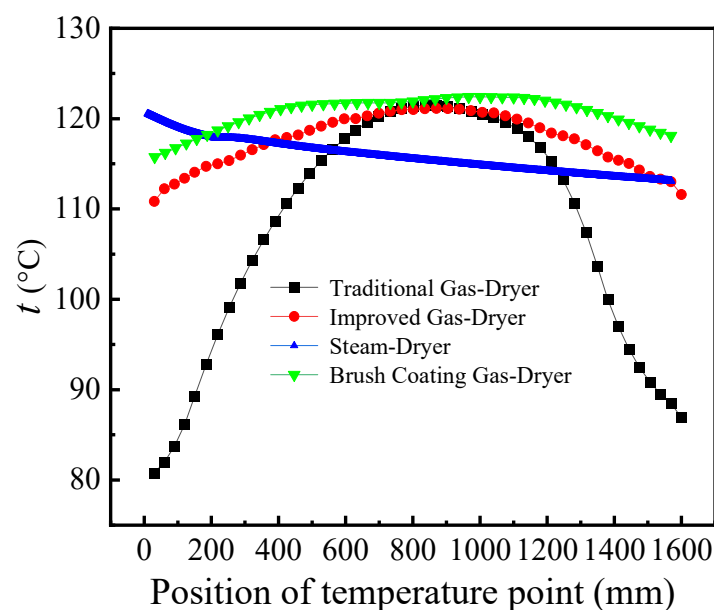


Figure 17. Comparison of simulated temperature distribution in the dryer with endothermic coating.

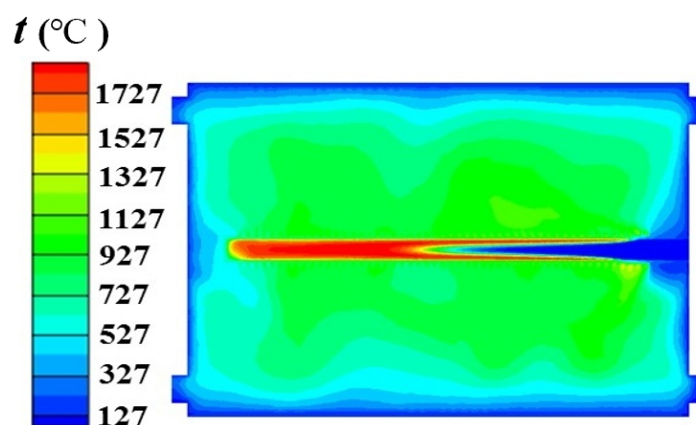


Figure 18. Internal temperature field at a drier's section along its axis with endothermic coating.

4. Conclusions

This paper takes the multi-channel steam dryer as the research background, takes the existing gas dryer as the research object, completes the optimization and improvement of its structure, focuses on analyzing the temperature distribution of the cylinder wall before and after the improvement of the steam dryer and traditional gas dryer, and draws the following conclusions:

- (1) The experimental measurement results are basically consistent with the numerical simulation results. The numerical simulation model can accurately calculate the temperature and changing trend of the dryer wall, which can meet the research needs, which proves the accuracy and reliability of the numerical simulation method;
- (2) The structural improvement of the traditional gas dryer mainly includes: (1) changing the two combustion tubes into one combustion tube without changing the combustion area of the combustion tube; (2) changing the symmetrical distribution of two fan-shaped smoke exits into six uniformly distributed circular smoke exits without changing the area of the smoke exits; (3) installing a stainless steel flue gas baffle at the flue gas outlet, and the flue gas baffle is polished by a fine mirror to enhance the infrared radiation reflectivity of the flue gas baffle and reduce diffuse reflection. After the structural optimization and improvement of the traditional gas dryer, the high-temperature flue gas generated by combustion is more evenly distributed inside the dryer, the wall temperature difference of the improved gas dryer is 13 °C, which is 57% lower than that of the traditional gas dryer, and the temperature evenness is increased from 66.7% to 89.6%. The wall temperature uniformity of the improved gas dryer is basically the same as that of the steam dryer.
- (3) In order to further improve the wall temperature uniformity of the improved gas dryer, the endothermic coating is applied to the inner wall with a low temperature at both ends of the dryer so as to reduce the temperature difference between the two ends and the middle position. The numerical simulation results based on the coating optimization scheme show that, compared with the improved gas dryer, the wall temperature difference is reduced from 13 °C to 7 °C, the temperature evenness is increased from 89.6% to 94.4%, and the maximum axial temperature difference of the cylinder wall is further reduced by 46%. It can be inferred theoretically that the coating optimization scheme can further improve the wall temperature uniformity of the improved gas dryer, and it is necessary to conduct experimental research on this scheme to prove its feasibility in the future.

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