Energy consumption analysis and simulation of waste heat recovery technology of ceramic rotary kiln

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Abstract. Ceramsite is widely used in the construction industry, insulation works and oil industry in China, and the manufacture equipment is mainly industrial kiln. In this paper, energy consumption analysis had been carried out through experimental test of a Ceramsite kiln in Henan province. Results showed that the discharge temperature of Ceramsite was about 1393K, and the waste heat accounted for 22.1% of the total energy consumption. A structure of cyclone preheater which recovered waste heat of the high temperature Ceramsite by blast cooling was designed. Then, using Fluent software, performance of the unit was simulated. The minimum temperature that Ceramsite could reach, heat dissipating capacity of Ceramsite, temperature at air outlet, wall temperature of the unit and pressure loss were analyzed. Performance of the designed unit under different inlet velocity was analyzed as well.

1. Introduction
Ceramsite, which is also called artificial light aggregate, is generally round or oval with the size of 5~20mm. The particles smaller than 5mm, namely ceramic sand, is mainly used for petroleum propping agent. In the past ten years in China, requirements of Ceramsite in quantity and variety are increasing rapidly, and the quality is also gradually improving[1]. The Ceramsite manufacture equipment in China is mainly industrial kiln especially rotary kiln, which uses the rotation of body to promote the material rolling, avoid bonding and strengthen the contact of flue gas and material.

Ceramsite rotary kiln has many good functions, while the energy consumption is relatively high. In current stage of China, the unit energy consumption using rotary kiln is mostly 4600~5030kJ/kg, which is 30%~40% higher than those in developed countries (generally 3140~3560 kJ/kg)[2]. Small scale production lines, low production technology and low equipment level are the main reasons. A comprehensive experimental and numerical research on thermal process and kiln burner in rotary kiln has been carried out[3-5], but there is little research focused on the waste heat recovery of Ceramsite products. In this paper, based on the field test of a Ceramsite rotary kiln, energy consumption of each part and energy balance analysis were carried out. A cyclone preheater was designed to recover waste heat of the high temperature Ceramsite, performance of the designed unit was simulated by Fluent software.

2. Rotary kiln test system and energy balance analysis
A typical domestic rotary kiln, including combustion chamber, rotary kiln body, ash hopper, underground flue and chimney, has been selected as the test object which mainly produces granular petroleum propping agent Ceramsite. The body of rotary kiln is totally 45m, can be divided into drying and preheating section, decomposition and exothermic section and firing section. The external and
internal diameter of the Ceramsite rotary kiln is 2.4m and 1.8m respectively, while the middle is the insulating layer made of refractory material. It is rotated at a certain angular velocity and two driving units are installed in the middle. The Ceramsite rotary kiln can be seen in Figure 1.

**Figure 1** Real object and Structural diagram of the rotary kiln

### 2.1. Field test system of rotary kiln

The head of diffusion burner locates in a small room above the discharge hopper, firing ceramic sand flows tumbling toward the direction of the burner under the action of slow rotation of the rotary kiln body, similar to the form of waterfall. Then ceramic sand product falls into cooling cylinder by the funnel-shaped collecting pail. The cooling cylinder which has a length of 10m is arranged in a vertical direction to the rotary kiln body and rotates slowly. Spray water is laid out above to reduce the temperature of ceramic sand. Inside the rotary kiln body, flame and flue gas flows to the ash hopper. After settling and dust removing, it comes into the bottom smoke exhaust flue, and then discharges from chimney. In the length direction of rotary kiln body, ceramic sand material is supplied from the opposite inlet of the right-side ash hopper, moving from the high side to the lower while tumbling slowly at the same time. High temperature flue gas flows from the low side to the higher, in contact with the ceramic sand material, so heat and mass transfer process occurs.

Depend on the variables required for the energy balance analysis of Ceramsite rotary kiln, variables has been tested in this paper, including ambient temperature, surface temperature of rotary kiln body, flue gas temperature, discharge temperature of Ceramsite, components of flue gas, amount of air and gas involved in the reaction of the burner.

### 2.2. Energy consumption analysis

Energy conversion process in Ceramsite rotary kiln is rather complicated. In this test, boundary of the control body was taken as the smoke exhaust ash hopper, surface of the rotary kiln body and the outer surface that Ceramsite just left the firing section. Energy input item of Ceramsite rotary kiln includes input heat of combustion air and gas involved in the reaction. Energy output item includes heat absorption of Ceramsite, heat of water evaporation, heat of Ceramsite carryover, heat loss of flue gas and heat loss of wall. Ceramsite rotary kiln is not stored for energy.

During the test, natural gas flow basically remained stable at an average of 347Nm$^3$/h. Temperature of discharge Ceramsite and the Ceramsite falling into grate were 1393K and 1103K respectively, while the average temperature of combustion air and outlet flue gas were 463K and 681K respectively. The energy output item of Ceramsite rotary kiln can be seen in Table 1 according to the test. During the experiment test, total energy input was 3456kW. It was calculated that there was a difference between the energy input and output of 6kW, which was within the acceptable error range, for some of the heat losses in furnace header and ash hopper had been ignored.

In all the energy output items from Table 1, heat of water evaporation and heat absorption of Ceramsite were the heat that must be consumed from raw material to ceramic product. Then thermal efficiency of the tested rotary kiln can be calculated to be 18.9%. It could be found that heat loss of wall was the main energy loss part of Ceramsite rotary kiln, while heat of Ceramsite carryover was also a considerable part. When discharge temperature of Ceramsite was 1393K, heat of Ceramsite carryover
accounted for 22.1% of the total energy output item. Recovery and utilization of Ceramsite waste heat can improve the thermal efficiency of Ceramsite rotary kiln to a large extent.

**Table 1.** Total energy output item of Ceramsite rotary kiln

| Energy output item | Heat of Ceramsite carryover (kW) | Heat of water evaporation (kW) | Absorption of Ceramsite (kW) | Heat loss of flue gas (kW) | Convective heat loss of wall (kW) | Radiative heat loss of wall (kW) | Total (kW)  |
|--------------------|----------------------------------|--------------------------------|-----------------------------|---------------------------|----------------------------------|---------------------------------|-----------|
| Heat (kW)          | 762                              | 138                            | 513                         | 815                       | 349                              | 873                             | 3450      |

Heat dissipation of high temperature Ceramsite is mainly carried out by convective heat transfer, blast cooling can be used to recover the waste heat. To get the better recovery efficiency, a type of cyclone preheater has been designed with consideration of the lightweight property of Ceramsite and recovery of high temperature air after heat transfer. The device is helpful to collect Ceramsite and the utilization of the waste heat recovery.

3. **Numerical simulation of heat recovery technology**

3.1. **Structure of waste heat recovery unit**

The designed waste heat recovery unit is similar to that of cyclone dust collector with four parts, inlet flow of Ceramsite and air, inverse cone-shaped cylinder, collection ash hopper of Ceramsite and upper flow outlet of high temperature air. The internal flow field is mainly divided into two strands, one is downward rotating along the wall, and the other is upward flow of the center internal spiral. SolidEdge software was used for 3D geometric modeling, and Gambit pretreatment software was used to divide grid of the model by Tgrid method. Grid number was 1082628, while the maximum distortion was below 0.7. The structure and grid division diagram of the waste heat recovery are shown in Figure 2.

**Figure. 2** Structure and Grid division diagram of the waste heat recovery unit

For this simulation condition, it was a flow containing dust that volume fraction of particle phase was less than 10%. Discrete phase model was chosen. The inlet boundary condition of continuous phase Ceramsite was set as Velocity Inlet conditions with the dust flow rate of 2m/s perpendicular to the entrance and inlet air temperature of 300K. The outlet boundary condition of air was set as Pressure-Outlet type. Boundary condition of the wall was No-slip conditions and Complete Smooth. The inlet of discrete phase Ceramsite was set as mass inlet with mass flow of 0.6kg/s and inlet Ceramsite temperature of 1393K. Boundary condition of the upper flow outlet was escape conditions, while the bottom collection ash hopper of Ceramsite was trapped conditions. Ceramsite and the surrounding wall of cylinder were reflect conditions. Radiative heat transfer model was chosen as DO model. The process was simulated with solid-flow heat transfer model, mainly focus on the flow field inside the heat exchanger and the heat exchange between the air and the ceramsite.
3.2. Flow Field Analysis
The simulated flow field trace is shown in Figure 3. We can see the downward external swirling flow along the wall and the upward internal swirling flow along the center, which is in agreement with the condition of cyclone dust collector and cyclone preheater. Separation efficiency of the unit depends on the state of swirling flow and particle size of Ceramsite. Since particle size of Ceramsite is larger relative to the powdery substance, Ceramsite is all trapped in this unit and does not move upward with the internal swirling of air, the separation effect is very good.

3.3. Internal temperature distribution
Internal temperature distribution of the heat exchanger is shown in Figure 4 to analyse the temperature variation of ceramsite and air. Heat transfer of Ceramsite and air mainly concentrates in the process of external swirling flow near the wall, especially at the initial stages of mixing, while the better heat transfer coefficient arising from the larger relative velocity and temperature difference between Ceramsite and the air blown. For the internal swirling flow, there is almost no heat transfer, the temperature distribution at the axis center is relatively uniform, which is 700K~850K. Through the calculation, the average temperature at air outlet is 729K, while the temperature of ceramsite after the heat exchange drops to 887K.

3.4. Temperature distribution of the wall
It can be found that the average temperature of heat transfer cylinder of the unit is about 730K~840K. Near the bottom collection ash hopper of Ceramsite, the wall temperature is about 870K, which is basically the same as the ceramsite temperature after heat exchange. At tangential inlet, the wall temperature is from 1000K to 1270K, due to the high temperature of ceramsite, especially in the lower wall of inlet, so the manufacture material here should be high temperature resistant.

3.5. Analysis under different inlet air velocity
Different inlet air velocity was selected while other conditions were identical to the preceding simulation, the results of Ceramsite state, air state and pressure loss were obtained, which are tabulated in Table 2. The increase of velocity affects the average residence time of Ceramsite in the heat transfer cylinder, there is no significant change in the average residence time when the air velocity does not exceed...
4.25 m/s, while the residence time suddenly increase to 3.9 s when velocity reaches 5 m/s. It could be found that air can blow off Ceramsite well at the velocity of 5 m/s, and Ceramsite can well conduct the downward external swirling flow along the wall of heat transfer cylinder with the air, extending the contact time of Ceramsite and air, and being conducive to the heat transfer, heat dissipating capacity of Ceramsite increases gradually. The minimum temperature that Ceramsite could reach and temperature at air outlet tend to decrease gradually as the velocity at air inlet increases. The change trend of the minimum temperature of Ceramsite is rapid when velocity exceeds 4.25 m/s. For the diameter of 1~3 mm, the unit could trap all the Ceramsite when velocity reaches 5 m/s. The pressure loss increases gradually from 6 Pa to 38 Pa with the change of velocity at air inlet, the value is comparable from the related literature[6], which can be used to guide fan selection.

Table 2: Results under different velocity conditions with Ceramsite flow 0.6 kg/s

| Parameters                              | Simulation results |
|-----------------------------------------|--------------------|
| Working air velocity (m/s)              | 2                  |
|                                         | 2.5                |
|                                         | 3.5                |
|                                         | 4.25               |
|                                         | 5                  |
| Minimum temperature Ceramsite could reach (K) | 887               |
|                                         | 826                |
|                                         | 759                |
|                                         | 718                |
|                                         | 468                |
| Average residence time in the unit (s)  | 2.4                |
|                                         | 2.2                |
|                                         | 1.9                |
|                                         | 1.8                |
|                                         | 3.9                |
| Heat dissipating capacity (kW)          | 213.3              |
|                                         | 223.4              |
|                                         | 235.1              |
|                                         | 241.3              |
|                                         | 272.4              |
| Trapped situation                       | All                |
|                                         | All                |
|                                         | All                |
|                                         | All                |
| Average temperature at air outlet (K)   | 729                |
|                                         | 666                |
|                                         | 576                |
|                                         | 536                |
|                                         | 508                |
| Pressure loss (Pa)                      | 6                  |
|                                         | 9                  |
|                                         | 18                 |
|                                         | 27                 |
|                                         | 38                 |

4. Conclusion
In this paper, based on the field test of Ceramsite rotary kiln, energy consumption of each part and energy balance analysis were carried out using the test data. A structure of cyclone preheater which recovered waste heat of the high temperature Ceramsite by blast cooling was designed. Then, using Fluent software, performance of the unit had been simulated, including the trend of the minimum temperature that Ceramsite could reach, heat dissipating capacity of Ceramsite, temperature at air outlet, average wall temperature and pressure loss with the change of velocity at the air inlet.

The main heat loss of Ceramsite rotary kiln is the heat of Ceramsite carryover, heat loss of flue gas and radiative heat loss of the wall, which accounts for 22.1%, 23.6% and 25.3% of the total energy output item respectively. When the discharge temperature of Ceramsite rotary kiln reaches 1393 K, the energy efficiency could be greatly improved if this part of energy is recovered.

Separation efficiency of the waste heat recovery unit of Ceramsite depends on the state of swirling flow and particle size of Ceramsite. Heat transfer of Ceramsite and air mainly concentrates in the process of the external swirling flow. The heat transfer process of high temperature Ceramsite and air is mainly concentrated in the upper part of heat transfer cylinder. For the diameter of 1~3 mm, the unit could trap all the Ceramsite in any case of air velocity, heat dissipating capacity of Ceramsite increases gradually with the inlet air velocity increasing.

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