Thermal efficiency modelling of the cement clinker manufacturing process

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Abstract

The cement clinker manufacturing process is a complex process which involves energy conversion and consumption. The objective of this study is to establish the thermal efficiency analytic model of this process. Energy flow models of the whole process and its three process units of raw material preheating & decomposition, clinker calcination, clinker cooling are established in this paper. The thermal efficiency of the whole process is quantitatively described based on the energy consumption fraction of each process unit. Energy consumption fractions of the three process units in a cement plant are 1.15, 0.43 and 0.47 respectively. It shows that the thermal efficiency of the raw material preheating & decomposition process unit has the greatest impact on the thermal efficiency of the whole process, successively followed by the clinker cooling and clinker calcination process units. Methods to improve the thermal efficiency of the whole process are discussed.

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1. Introduction

The cement industry is a typical energy intensive industry with energy accounting for 50%–60% of production costs [1]. Scholars have studied on energy models and energy conservation measures of various high energy consumption industries such as the cement industry. In the aspect of energy consumption modelling, Jebaraj and Iniyan summarized the existing energy models, including the energy demand supply model, the energy consumption forecasting model, the energy optimization model and the energy dissipation model [2]. In addition, some scholars advanced the energy consumption model [3,4] and the energy flow model [5,6] which were independent of specific energy forms and energy equipment. On the other hand, some researches advanced the energy flow models in the manufacturing processes of cement, steel and aluminum [7–10]. They further analysed the impacts of relevant changes on energy consumptions. In the aspect of energy efficiency models, Giacone and Mancò defined the energy efficiencies in industrial processes [11]. Some scholars analysed the useful energy for manufacturing processes [12,13] and established the energy efficiency indexes of industrial processes [14]. Some researches discussed the energy conservation measures of process units from the perspective of manufacturing technology and equipment [15–18]. The above-mentioned literatures analysed the high energy consumption industries such as the cement industry in the aspects of energy models, energy efficiencies and energy conservation measures. All of these results played an important role in the implementation of energy conservations and emission reductions. However, the previous literatures did not consider the energy efficiency relationships between industrial processes and their process units, and lacked corresponding theoretical guidance on the implementation of energy conservation measures. In addition, the energy conservation measures in above literatures were based on the manufacturing techniques and the production equipment of industrial processes. For stable manufacturing processes, the optimal control of process parameters is an effective method for improving the energy efficiency of the cement clinker manufacturing process. Therefore, the establishment of energy efficiency analytic relations between the cement clinker manufacturing process and its process units has a great significance for analysing and formulating reasonable energy efficiency improvement measures.
The cement clinker manufacturing process consists of three process units, including the raw materials preheating & decomposition, clinker calcination and clinker cooling. In order to analyse the energy efficiency relationship between the cement clinker manufacturing process and its three process units, the energy flow models of the whole process and each process unit are established. The thermal efficiency analytic model of the whole process is quantitatively described based on the energy flow models and the energy consumption fractions of its three process units. It is found that improving the decomposition rate of raw materials fed into kiln, stabilizing the temperature of the rotary kiln burning zone and improving the temperature of the secondary and tertiary air are effective approaches to improve the thermal efficiency of the whole process.

2. Brief introduction of the cement clinker manufacturing process

There are four main devices used in the cement clinker manufacturing process, namely preheater, calciner, rotary kiln and grate cooler, achieving raw materials preheating and decomposing, clinker burning and cooling respectively. The manufacturing system, considered for modelling, is schematically shown in Fig. 1. The raw materials decompose in the calciner after preheated by the cyclone preheater, and then, with the updraft, enter into the last level cyclone for gas–solid biphasic separation. Later the raw materials enter into the rotary kiln for calcination. Due to the inclined placement and the continuous rotation of rotary kiln, the raw materials continuously move to the grate cooler, and form clinker after the high temperature calcination through the rotary kiln burning zone. Finally, the hot clinker falls towards to grate cooler for rapid cooling. During the cement clinker manufacturing process, the airflow direction is just opposite to the materials flow direction [7].

3. Energy flow modelling of the cement clinker manufacturing process

3.1. The energy flow model of process units

The cement clinker manufacturing process is a mass transfer and energy conversion process. There are six categories of energy flow in each process unit according to the energy sources and destinations. The definitions and descriptions of the energy flow model in process units are shown in Table 1.

The input–output relationship of the energy flow in each process unit is shown in Fig. 2. The energy balance in a process unit is:

\[ E_u + E_i + E_r = E_d + E_e + E_l + E_r \]  

The energy consumption of a process unit is:

Fig. 1. Schematic diagram of the cement clinker manufacturing process.
Table 1

<table>
<thead>
<tr>
<th>Energy flow</th>
<th>Description for energy flow</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream energy flow</td>
<td>Energy is brought by materials from upstream process units</td>
<td>$E_u$</td>
</tr>
<tr>
<td>Imposed energy flow</td>
<td>Energy is supplied by energy inputs but no other process units</td>
<td>$E_i$</td>
</tr>
<tr>
<td>Internal reused energy flow</td>
<td>Energy is recovered in the internal process unit</td>
<td>$E_r$</td>
</tr>
<tr>
<td>Downstream energy flow</td>
<td>Energy is taken away by products to downstream process units</td>
<td>$E_d$</td>
</tr>
<tr>
<td>External reused energy flow</td>
<td>Energy is recovered for external process units</td>
<td>$E_e$</td>
</tr>
<tr>
<td>Lost energy flow</td>
<td>Energy is lost in process units through emission or consumption</td>
<td>$E_l$</td>
</tr>
</tbody>
</table>

$E_c = E'_c - E''_c = (E_u + E_i + E_r) - (E_r + E_e)$  

where $E_c$ is the energy consumption of a process unit (kJ), $E_i$ is the energy inputs of a process unit (kJ), $E'_c$ is the reused energy of a process unit (kJ).

The energy efficiency of energy consumption process units is:

$$\eta_c = \frac{E_d}{E_c} \times 100\%$$  

where $\eta_c$ is the energy efficiency of energy consumption process units (%).

The energy efficiency of energy conversion process units is:

$$\eta_t = \frac{E_d + E_e}{E_c} \times 100\%$$  

where $\eta_t$ is the energy efficiency of energy conversion process units (%). [11]

3.2. The scope of energy flow modelling of the cement clinker manufacturing process

The schematic diagram of thermal balance in the cement clinker manufacturing process is shown in Fig. 3. The scope of energy flow models is from the exhaust gas export of preheater to the clinker export of grate cooler. The functions of preheater and calciner are raw materials preheating and decomposition, so they will be considered as a whole. Thermal energy is the main energy consumption in the cement clinker manufacturing process, so thermal energy is the only energy category for consideration in this study. Other forms of energies are not considered here.

3.3. Energy flow model of the cement clinker manufacturing process

The thermal energy income and expenditure diagram of the cement clinker manufacturing process is shown in Fig. 3, and the thermal energy unit is kJ kg$^{-1}$. The thermal energy balance relationship in the cement clinker manufacturing process is shown in Table 2. The cement clinker manufacturing process can be seen as a “big” process unit. According to the thermo technical calibration data of a real cement plant shown in Appendix A, the thermal energy balance in the cement clinker manufacturing process is shown in Fig. 4.where:
\[ E_i = Q_{sR} + Q_s + Q_{sk} \quad (5) \]
\[ E_i = Q_{sR} + Q_s + Q_{sk} + Q_{1k} + Q_{Lok} \quad (6) \]
\[ E_f = Q_{1k} \quad (7) \]
\[ E_d = Q_{Lh} \quad (8) \]
\[ E_e = Q_{mmf} + Q_{mmff} \quad (9) \]
\[ E_l = Q_{ss} + Q_{Lsh} + Q_f + Q_{fh} + Q_{pk} + Q_{Lfh} + Q_B + Q_{qt} \quad (10) \]

The energy consumption of the cement clinker manufacturing process is:

![Schematic diagram of the thermal energy balance in the cement clinker manufacturing process.](image)

Table 2: Thermal energy balance of the cement clinker manufacturing process.

<table>
<thead>
<tr>
<th>Thermal energy input</th>
<th>Symbol</th>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion heat of fuel</td>
<td>( Q_{sR} )</td>
<td>Formation heat of clinker</td>
</tr>
<tr>
<td>Sensible heat of fuel</td>
<td>( Q_s )</td>
<td>Sensible heat of clinker out of grate cooler</td>
</tr>
<tr>
<td>Combustion heat of the combustible materials in raw materials</td>
<td>( Q_r )</td>
<td>Sensible heat of exhaust gas at preheater outlet</td>
</tr>
<tr>
<td>Sensible heat of raw materials</td>
<td>( Q_{Lsh} )</td>
<td>Sensible heat of fly ashes at preheater outlet</td>
</tr>
<tr>
<td>Sensible heat of returning ashes fed into preheater</td>
<td>( Q_{1k} )</td>
<td>Sensible heat of exhaust air out of grate cooler</td>
</tr>
<tr>
<td>Sensible heat of primary air</td>
<td>( Q_{Lk} )</td>
<td>Sensible heat of fly ashes at grate cooler outlet</td>
</tr>
<tr>
<td>Sensible heat of cooling air into grate cooler</td>
<td>( Q_{Lk} )</td>
<td>Sensible heat of fly ashes in air draft for coal grinding</td>
</tr>
<tr>
<td>Sensible heat of air brought with raw materials</td>
<td>( Q_{Lok} )</td>
<td>Heat dissipation of system surface</td>
</tr>
<tr>
<td>Sensible heat of seeping air</td>
<td>( Q_{sk} )</td>
<td>Other heat expenditures</td>
</tr>
</tbody>
</table>

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<tr>
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<td>( Q_{Lk} )</td>
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<tr>
<td>Sensible heat of air brought with raw materials</td>
<td>( Q_{Lok} )</td>
<td>Heat dissipation of system surface</td>
</tr>
<tr>
<td>Sensible heat of seeping air</td>
<td>( Q_{sk} )</td>
<td>Other heat expenditures</td>
</tr>
</tbody>
</table>

\[ E_c = E'_c - E''_c = (E_u + E_i + E_r) - (E_i + E_u) \]
\[ = Q_{sR} + Q_s + Q_{sh} + Q_{ok} + Q_R + Q_f + Q_{lo} - Q_{mmf} - Q_{mmf} \]
\[ = Q_{sh} + Q_{ss} + Q_{sh} + Q_f + Q_{pk} + Q_{ph} + Q_b + Q_{bf} \]
\[ \text{(11)} \]

The thermal efficiency of the cement clinker manufacturing process is:
\[ \eta_c = \frac{E_d}{E_c} \times 100\% = \frac{Q_{sh}}{Q_{sh} + Q_{ss} + Q_{sh} + Q_f + Q_{pk} + Q_{ph} + Q_b + Q_{bf}} \times 100\% \]
\[ \text{(12)} \]

### 3.4. Energy flow models of the three process units in the cement clinker manufacturing process

(1) The raw materials preheating & decomposition process unit is composed of preheater, calciner and some other equipment. In this process unit, the raw materials go through dehydration, preheating, as well as most carbonate decomposition and then enter into rotary kiln for burning. The raw materials preheating & decomposition process unit is a typical energy consumption process unit and its thermal energy balance is shown in Table 3.

where:
\[ E_{uP} = Q_{sR} + Q_s + Q_{q} + Q_{3k} + Q_{sh} \]
\[ \text{(13)} \]
\[ E_{IP} = Q_{sR,P} + Q_{s,P} + Q_{lok,P} \]
\[ \text{(14)} \]
\[ E_{RP} = Q_{yh} \]
\[ \text{(15)} \]
\[ E_{dP} = Q_{ry} + Q_{f} \]
\[ \text{(16)} \]
\[ E_{LP} = Q_{ss} + Q_f + Q_{ph} + Q_{r,P} \]
\[ \text{(17)} \]

P indicates the preheating & decomposition process unit.

The energy consumption of the preheating & decomposition process unit is:

| Thermal energy balance of the raw materials preheating & decomposition process unit. |
|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| **Thermal energy input**                | **Thermal energy output**                                                                                                                                                          |
| Item                                    | Symbol                                                                                                                           | Item                                    | Symbol                                                                 |
| Combustion heat of fuel                 | \( Q_{sR} \)                                                                                                                    | Heat consumption of water evaporation in raw materials | \( Q_{sw} \)                                                                 |
| Sensible heat of fuel                   | \( Q_s \)                                                                                                                       | Sensible heat of fly ashes at preheater outlet | \( Q_{sh} \)                                                                 |
| Combustion heat of the combustible materials in raw materials | \( Q_{sh} \)                                                                                                                  | Sensible heat of exhaust gas at preheater outlet | \( Q_f \)                                                                 |
| Sensible heat of raw materials          | \( Q_{ok} \)                                                                                                                   | Heat consumption for carbonate decomposition | \( Q_{rP} \)                                                                 |
| Sensible heat of returning ashes fed into preheater | \( Q_{lo} \)                                                                                                                   | Sensible heat of materials into the rotary kiln | \( Q_{ry} \)                                                                 |
| Sensible heat of flue gas in kiln tail   | \( Q_{pk} \)                                                                                                                   | Heat dissipation of system surface        | \( Q_{b,P} \)                                                                 |
| Sensible heat of tertiary air           | \( Q_{ph} \)                                                                                                                   |                                                                                       |                                                                                                                           |
| Sensible heat of air brought with raw materials | \( Q_{b} \)                                                                                                                   |                                                                                       |                                                                                                                           |
| Sensible heat of seeping air            | \( Q_{lok,P} \)                                                                                                                 |                                                                                       |                                                                                                                           |
\[
E_{c,p} = E_{c,p} - E_{c,p}^* = (E_{u,p} + E_{i,p} + E_{r,p}) - (E_{r,p} + E_{s,p})
\]
\[
= Q_{fr} + Q_{qf} + Q_{sk} + Q_{sk} + Q_{ry} + Q_{p} + Q_{rok}
\]
\[
= Q_{fy} + Q_{qf} + Q_{sy} + Q_{sy} + Q_{f} + Q_{f} + Q_{p} 
\]
\[
(18)
\]

The thermal efficiency of the preheating & decomposition process unit is:

\[
\eta_{c,p} = \frac{E_{d,p}}{E_{c,p}} \times 100\% = \frac{E_{d,p}}{(E_{u,p} + E_{i,p} + E_{r,p}) - (E_{r,p} + E_{s,p})} \times 100\% 
\]
\[
= \frac{Q_{qf} + Q_{qy}}{Q_{fy} + Q_{qf} + Q_{sy} + Q_{sy} + Q_{f} + Q_{f} + Q_{p}} \times 100\%
\]

where \(\eta_{c,p}\) is the thermal efficiency of the preheating & decomposition process unit (%).

According to Equations (18) and (19), the main energy consumptions of the preheating & decomposition process unit are the carbonate decomposition and all forms of heat expenditures. So increasing the carbonate decomposition rate and the temperature of materials into kiln is an effective way to improve the thermal efficiency of this process unit.

(2) The clinker calcination is an important energy consumption process unit in the cement clinker manufacturing process, including rotary kiln, kiln hood and some auxiliary equipment. In this process unit, the materials, coming from the preheating & decomposition process unit, complete the heat exchange with high temperature reverse airflow. Finally, the materials are sintered to clinker. Thermal energy balance in this process unit is shown in Table 4.

where:

\[
E_{u,K} = Q_{fy} + Q_{sk}
\]
\[
E_{i,K} = Q_{ry} + Q_{rok}
\]
\[
E_{d,K} = Q_{sy} + Q_{yq}
\]
\[
E_{e,K} = Q_{qf}
\]
\[
E_{f,K} = Q_{yq}
\]
\[
K \text{ indicates the clinker calcination process unit.}
\]

The energy consumption of the clinker calcination process unit is:

\[
E_{c,K} = E_{c,K} - E_{c,K}^* = (E_{u,K} + E_{i,K} + E_{r,K}) - (E_{r,K} + E_{e,K}) = Q_{sy} + Q_{yq} + Q_{yq}
\]

\[
(25)
\]

The thermal efficiency of the clinker calcination process unit is:

\[
\eta_{c,K} = \frac{E_{d,K}}{E_{c,K}} \times 100\% = \frac{E_{p,K}}{(E_{u,K} + E_{i,K} + E_{r,K}) - (E_{r,K} + E_{e,K})} \times 100\% = \frac{Q_{sy} + Q_{yq} + Q_{yq}}{Q_{sy} + Q_{yq} + Q_{yq}} \times 100\%
\]

where \(\eta_{c,K}\) is the energy efficiency of the clinker calcination process unit (%).

According to Equations (25) and (26), the main energy consumptions of the clinker calcination process unit are the sensible heat of clinker out of rotary kiln and the heat dissipation of kiln surface. Increasing the temperature of clinker out of kiln and reducing the heat dissipation of kiln surface are effective methods to improve the thermal efficiency of this process unit.

(3) The function of the clinker cooling process unit is to quench the clinker out of kiln and recover the heat of hot clinker. It involves grate cooler, cooling fan and some other equipment. The clinker cooling process unit is a typical energy conversion process unit and its thermal energy balance is shown in Table 5.

Table 4

<table>
<thead>
<tr>
<th>Thermal energy input</th>
<th>Symbol</th>
<th>Item</th>
<th>Thermal energy output</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion heat of fuel</td>
<td>(Q_{r,K})</td>
<td>Heat absorbed in the formation of clinker</td>
<td>(Q_{r})</td>
<td></td>
</tr>
<tr>
<td>Sensible heat of fuel</td>
<td>(Q_{r})</td>
<td>Sensible heat of flue gas in kiln tail</td>
<td>(Q_{qf})</td>
<td></td>
</tr>
<tr>
<td>Sensible heat of materials into the rotary kiln</td>
<td>(Q_{sy})</td>
<td>Sensible heat of clinker out of rotary kiln</td>
<td>(Q_{r})</td>
<td></td>
</tr>
<tr>
<td>Sensible heat of secondary air</td>
<td>(Q_{yq})</td>
<td>Heat dissipation of system surface</td>
<td>(Q_{sy})</td>
<td></td>
</tr>
<tr>
<td>Sensible heat of primary air</td>
<td>(Q_{yq})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensible heat of seeping air</td>
<td>(Q_{yq})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(Q_{r,K}\) is the energy efficiency of the clinker calcination process unit (%).
where:

\[ E_{u,C} = Q_{Ysh} \]  
\[ E_{i,C} = Q_{Lk} + Q_{LOk,C} \]  
\[ E_{e,C} = Q_{2k} + Q_{3k} + Q_{mmf} + Q_{mmff} \]  
\[ E_{i,C} = Q_{Lsh} + Q_{pk} + Q_{Lfh} + Q_{B,C} \]  

C indicates the clinker cooling process unit.

The energy consumption of the clinker cooling process unit is:

\[ E_{e,C} = E'_{e,C} = (E_{u,C} + E_{i,C} + E_{r,C}) - (E_{r,C} + E_{e,C}) = Q_{Lsh} + Q_{pk} + Q_{Lfh} + Q_{B,C} \]  

The thermal efficiency of the clinker cooling process unit is:

\[ \eta_{t,C} = \frac{E_{d,C} + E_{e,C}}{E_{e,C}} \times 100\% = \frac{Q_{2k} + Q_{3k} + Q_{mmf} + Q_{mmff}}{Q_{Ysh} + Q_{Lk} + Q_{LOk,C}} \times 100\% \]  

where \( \eta_{t,C} \) is the energy efficiency of the clinker cooling process unit (\%).

According to Equations (31) and (32), the main energy consumptions of the clinker cooling process unit are the sensible heat of clinker out of grate cooler and the sensible heat of exhaust air and fly ashes. Increasing the temperature of secondary air and tertiary air is the effective method to increase the thermal exchange efficiency of this process unit.

### 3.5. Energy flow diagram of the cement clinker manufacturing process

According to the thermo technical calibration data of the real cement plant mentioned in Fig. 4, the energy flow diagram of the real cement clinker manufacturing process is shown in Fig. 5. The thermal energy unit is kJ kg\(^{-1}\).

---

**Table 5**

Thermal energy balance of the clinker cooling process unit.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Item</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible heat of clinker into grate cooler</td>
<td>( Q_{Ysh} )</td>
<td>Sensible heat of air draft for coal grinding</td>
<td>( Q_{mmf} )</td>
</tr>
<tr>
<td>Sensible heat of cooling air into grate cooler</td>
<td>( Q_{Lk} )</td>
<td>Sensible heat of fly ashes in air draft for coal grinding</td>
<td>( Q_{mmff} )</td>
</tr>
<tr>
<td>Sensible heat of seeping air</td>
<td>( Q_{LOk,C} )</td>
<td>Sensible heat of secondary air</td>
<td>( Q_{2k} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensible heat of tertiary air</td>
<td>( Q_{3k} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensible heat of exhaust air out of grate cooler</td>
<td>( Q_{Lfh} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensible heat of fly ashes at grate cooler outlet</td>
<td>( Q_{pk} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sensible heat of clinker out of grate cooler</td>
<td>( Q_{Lsh} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heat dissipation of system surface</td>
<td>( Q_{B,C} )</td>
</tr>
</tbody>
</table>

---

**Fig. 5. Complete energy flow diagram of a real cement clinker manufacturing process.**
4. Thermal efficiency modelling of the cement clinker manufacturing process

The cement clinker manufacturing process is a gas–solid biphasic countercurrent heat exchanging system and the thermal efficiencies of the three process units are both interdependent and interactional. Therefore, the study on the thermal efficiency should not only concern the whole system but also consider the coordinated operation of its three process units. In this section, the analytic relation model between the thermal efficiency of the whole process and the thermal efficiencies of its three process units is established. The energy consumption fraction of each process unit is proposed to estimate the contribution rate of thermal energy efficiency.

4.1. Thermal efficiency analytic model of the cement clinker manufacturing process

4.1.1. Assumptions of the thermal efficiency analytic model

(1) The cement clinker manufacturing process is in stable state.
(2) The thermal efficiency unit is kJ kg⁻¹.
(3) Take zero Celsius degree as the reference temperature.
(4) Not consider the other heat expenditures $Q_{\text{fr}}$. 

4.1.2. Theoretical derivation of the thermal efficiency analytical model

The thermal efficiency of the cement clinker manufacturing process is:

$$\eta_c = \frac{Q_{\text{sh}}}{Q_{\text{sh}} + Q_{\text{sl}} + Q_{\text{sh}} + Q_f + Q_{\text{sh}} + Q_{pk} + Q_{fh} + Q_B} \times 100\%$$

$$= \left(1 - \frac{Q_{\text{sh}} + Q_{\text{sl}} + Q_f + Q_{\text{sh}} + Q_{pk} + Q_{fh} + Q_B}{E_c}\right) \times 100\%$$

$$= \left(1 - \frac{Q_{\text{sh}} + Q_f + Q_{fh} + Q_{B,P}}{E_c} - \frac{Q_{B,K}}{E_c} - \frac{Q_{\text{sh}} + Q_{pk} + Q_{fh} + Q_B}{E_c}\right) \times 100\%$$

(33)

where $Q_{\text{sh}} + Q_f + Q_{fh} + Q_{B,P}$ is the thermal energy loss in the raw materials preheating & decomposition process unit, $Q_{B,K}$ is the thermal energy loss in the clinker calcination process unit, $Q_{\text{sh}} + Q_{pk} + Q_{fh} + Q_B$ is the thermal energy loss in the clinker cooling process unit. The relationships between the thermal energy loss of each process unit and the thermal efficiency of the relevant process unit are as follows:

$$Q_{\text{sh}} + Q_f + Q_{fh} + Q_{B,P} = E_{c,P}(1 - \eta_{c,P})$$

(34)

$$Q_{B,K} = E_{c,K}(1 - \eta_{c,K})$$

(35)

$$Q_{\text{sh}} + Q_{pk} + Q_{fh} + Q_B = E_{c,C}(1 - \eta_{c,C})$$

(36)

Combining Equations (34)–(36) with Equation (33), we can obtain Equation (37).

$$\eta_c = \left[1 - \frac{E_{c,P}(1 - \eta_{c,P})}{E_c} - \frac{E_{c,K}(1 - \eta_{c,K})}{E_c} - \frac{E_{c,C}(1 - \eta_{c,C})}{E_c}\right] \times 100\%$$

$$= \left[1 - VEP(1 - \eta_{c,P}) - VEK(1 - \eta_{c,K}) - VEC(1 - \eta_{c,C})\right] \times 100\%$$

(37)

where $VE_P = E_{c,P}/E_c$, $VE_K = E_{c,K}/E_c$, $VE_C = E_{c,C}/E_c$ are the ratios of the energy consumption of each process unit and the total consumption of the cement clinker manufacturing process respectively. We define $VE_P = E_{c,P}/E_c$, $VE_K = E_{c,K}/E_c$ and $VE_C = E_{c,C}/E_c$ as the “energy consumption fraction”.

Energy consumption fraction

**Fig. 6.** Energy consumption fractions of the three process units in a real cement clinker manufacturing process.
fraction” of each process unit. The clinker cooling process unit is an energy conversion process, and can be considered as a “special” energy consumption process unit. The “energy consumption” is $E_{C_{CL}}$ and the “energy output” is $E_{C_{CL}}'$. Equation (38) is obtained after the collation of Equation (37).

$$\eta_{C} = \left(1 + VE_{P} \times \eta_{C,P} + VE_{K} \times \eta_{C,K} + VE_{C} \times \eta_{C,C} - VE_{P} - VE_{K} - VE_{C}\right) \times 100\%$$

(38)

4.2. Analysis and validation of the thermal efficiency analytic model

(1) Relationships between the thermal efficiency of the cement clinker manufacturing process and the thermal efficiencies of its three process units

According to Equation (38), there is a positive linear correlation between the thermal efficiency of the cement clinker manufacturing process and the thermal efficiencies of its three process units. The improvement of thermal efficiency of any process unit can improve the thermal efficiency of the whole process. The larger energy consumption fraction of process units is, the greater impact on the thermal efficiency of the cement clinker manufacturing process has. According to the thermo technical calibration data of the real cement plant mentioned in Fig. 5, energy consumption factions and thermal efficiencies of the three process unit, shown in Fig. 6 and Fig. 7, are calculated.

According to Fig. 6, the energy consumption faction of the raw materials preheating & decomposition process unit is largest, successively followed by the ones of the clinker cooling process unit and the clinker calcination process unit. It indicates that the raw materials preheating & decomposition process unit consumes the most thermal energy. The clinker cooling process unit is an energy conversion process that does not consume the imposed thermal energy. In this real cement clinker manufacturing process, the raw materials preheating & decomposition process unit consumes 72.85% (1.1539/(1.1539 + 0.43) × 100%) of the imposed thermal energy. In practice, thermal energy consumed in the raw materials preheating & decomposition process unit accounts for 68%–75% of thermal energy cost. The calculation results of the model match the actual situation. According to Fig. 7, the thermal efficiency of the clinker calcination process unit is the highest, successively followed by the ones of the raw materials preheating & decomposition process unit and the clinker calcination process unit. The adoption of appropriate measures to improve the thermal efficiency of the raw materials preheating & decomposition process unit is crucial to improve the thermal efficiency of the whole process. The thermal efficiency of the clinker cooling process unit (69.47%) calculated by the model is equal to the thermo technical calibration data shown in Appendix B and has huge rise space. So, improving the thermal efficiency of the clinker cooling can increase the recovery of thermal energy and reduce the imposed thermal energy. According to Equation (38), the total thermal efficiency of this real process is 54.44%. It is slightly higher than the thermal efficiency calculated by the thermo technical calibration data (53.04%). The reason is that the thermal energy used for coal mill is calculated as the recycled energy for other use while it is calculated as the heat loss in thermo technical standard. The thermal efficiency analytic model can reflect the reality of the cement clinker manufacturing process.

(2) Measures to improve the thermal efficiency of the cement clinker manufacturing process.

For the raw materials preheating & decomposition process unit, due to the limitation of technology and equipment, the outlet temperature of calciner is constant, i.e. the material temperature that enters into rotary kiln is basically constant. In order to improve the thermal efficiency of this process unit, the decomposition rate of the raw materials fed into kiln should be improved. For the improvement of decomposition rate of the raw materials fed into kiln, feed quantity of the raw materials, rotary speed of the fan at the kiln tail, tertiary air temperature and tertiary air quantity can be adjusted so as to reach the best gas–solid reaction rate. According to the thermal efficiency equation of the clinker calcination process unit, improving the material temperature out of kiln and reducing the heat dissipation of the rotary kiln are effective ways to improve the thermal efficiency. However, in the steady working conditions, the temperature of rotary kiln burning zone is 1300 °C–1450 °C. The temperature rise of the burning zone will inevitably increase the amount of coal fed, which will increase the liquid phase quantity of clinker in rotary kiln. Meanwhile, the temperature rise of the burning zone will increase the heat dissipating capacity of kiln body [19,20]. So, only $Q_{cl}$ value can be improved. $Q_{cl}$ is mainly impacted by decomposition rate of the raw materials fed into kiln. The high decomposition rate fed into kiln will lead to high $Q_{cl}$ value and high thermal efficiency of the clinker
calcination process unit. Therefore, the improvement of the decomposition rate of raw materials fed into kiln can improve thermal efficiency of the raw material preheating & decomposition process unit and the clinker calcination process unit at the same time. According to the thermal efficiency equation of the clinker cooling process unit, raising secondary air temperature and tertiary air temperature is the method to improve the thermal energy recovery efficiency. Gas–solid heat exchange theory of the cement clinker cooling process unit shows that the reasonable grading of cooling air quantity and air speed is the primary factor for raising the secondary and tertiary air temperature.

5. Conclusions

In this paper, energy flow models of the cement clinker manufacturing process and its three process units are established. The following conclusions are obtained based on the thermal efficiency analytic model of the cement clinker manufacturing process.

(1) There is a positive linear correlation between the thermal efficiency of the cement clinker manufacturing process and the thermal efficiencies of its three process units in the steady state conditions. The improvement of thermal efficiency of any process unit can improve the thermal efficiency of the whole process.

(2) The impact degree of each process unit to the thermal efficiency of the whole process depends on the energy consumption faction of each process unit. According to the thermo technical calibration data of a real cement plant, the energy consumption fraction of the raw materials preheating & composition process unit is the greatest, successively followed by the ones of the clinker cooling process unit and the clinker calcination process unit. The thermal efficiency calculated by the thermal efficiency analytic model can reflect the reality of the cement clinker manufacturing process.

(3) Increasing the decomposition rate of raw materials fed into kiln can improve the thermal efficiency of the raw materials preheating & decomposition process unit as well as the thermal efficiency of the clinker calcination process unit. Stabilizing the temperature of rotary kiln burning zone and improving the secondary and tertiary air temperature are also effective methods to improve the thermal efficiency of the whole process.

Acknowledgements

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Appendix A. The thermo technical calibration data of a real cement clinker manufacturing process in China

<table>
<thead>
<tr>
<th>Thermal energy input</th>
<th>kJ/kg</th>
<th>%</th>
<th>Thermal energy output</th>
<th>kJ/kg</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Item</td>
<td></td>
<td></td>
<td>No. Item</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Combustion heat of fuel</td>
<td>3059.67</td>
<td>94.38</td>
<td>1 Formation heat of clinker</td>
<td>1719.37</td>
<td>53.04</td>
</tr>
<tr>
<td>2 Sensible heat of fuel</td>
<td>8.35</td>
<td>0.26</td>
<td>2 Sensible heat of clinker out of grate cooler</td>
<td>86.81</td>
<td>2.68</td>
</tr>
<tr>
<td>3 Combustion heat of the combustible materials in raw materials</td>
<td>41.56</td>
<td>1.28</td>
<td>3 Heat consumption of water evaporation in raw materials</td>
<td>47.36</td>
<td>1.46</td>
</tr>
<tr>
<td>4 Sensible heat of returning ashes fed into preheater</td>
<td>5.00</td>
<td>0.15</td>
<td>4 Sensible heat of exhaust gas at preheater outlet</td>
<td>705.5</td>
<td>21.76</td>
</tr>
<tr>
<td>5 Sensible heat of raw materials</td>
<td>25.02</td>
<td>0.77</td>
<td>5 Sensible heat of fly ashes at preheater outlet</td>
<td>35.61</td>
<td>1.10</td>
</tr>
<tr>
<td>6 Sensible heat of primary air</td>
<td>3.26</td>
<td>0.10</td>
<td>6 Sensible heat of exhaust air out of grate cooler</td>
<td>424.51</td>
<td>13.10</td>
</tr>
<tr>
<td>7 Sensible heat of cooling air into grate cooler</td>
<td>93.55</td>
<td>2.89</td>
<td>7 Sensible heat of fly ashes at grate cooler outlet</td>
<td>7.26</td>
<td>0.22</td>
</tr>
<tr>
<td>8 Sensible heat of air brought with raw materials</td>
<td>4.78</td>
<td>0.15</td>
<td>8 Sensible heat of fly ashes in air draft for coal grinding</td>
<td>0.41</td>
<td>0.01</td>
</tr>
<tr>
<td>9 Sensible heat of seeping air</td>
<td>3.46</td>
<td>0.11</td>
<td>9 Sensible heat of air draft for coal grinding</td>
<td>27.59</td>
<td>0.85</td>
</tr>
<tr>
<td>10 Heat dissipation of system surface</td>
<td>263.23</td>
<td>8.12</td>
<td>11 Other heat expenditures</td>
<td>−73</td>
<td>−2.25</td>
</tr>
<tr>
<td>12 Total thermal energy input</td>
<td>3241.65</td>
<td>100.00</td>
<td>12 Total thermal energy output</td>
<td>3241.65</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Total energy efficiency: 53.04%

Appendix B. The thermo technical calibration data of a real clinker cooling process unit

<table>
<thead>
<tr>
<th>Thermal energy input</th>
<th>kJ/kg</th>
<th>%</th>
<th>Thermal energy output</th>
<th>kJ/kg</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Item</td>
<td></td>
<td></td>
<td>No. Item</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Sensible heat of clinker into grate cooler</td>
<td>1448.55</td>
<td>94.13</td>
<td>1 Sensible heat of exhaust air out of grate cooler</td>
<td>444.76</td>
<td>28.90</td>
</tr>
<tr>
<td>2 Sensible heat of cooling air into grate cooler</td>
<td>93.55</td>
<td>6.08</td>
<td>2 Sensible heat of fly ashes at grate cooler outlet</td>
<td>7.26</td>
<td>0.47</td>
</tr>
<tr>
<td>3 Sensible heat of seeping air</td>
<td>−3.29</td>
<td>−0.21</td>
<td>3 Sensible heat of secondary air</td>
<td>434.51</td>
<td>28.24</td>
</tr>
<tr>
<td>4 Sensible heat of tertiary air</td>
<td>606.89</td>
<td>39.44</td>
<td>4 Sensible heat of tertiary air</td>
<td>606.89</td>
<td>39.44</td>
</tr>
<tr>
<td>5 Sensible heat of clinker out of grate cooler</td>
<td>86.81</td>
<td>5.64</td>
<td>5 Sensible heat of clinker out of grate cooler</td>
<td>86.81</td>
<td>5.64</td>
</tr>
<tr>
<td>6 Heat dissipation of system surface</td>
<td>8.07</td>
<td>0.52</td>
<td>6 Heat dissipation of system surface</td>
<td>8.07</td>
<td>0.52</td>
</tr>
<tr>
<td>7 Sensible heat of air draft for coal grinding</td>
<td>27.59</td>
<td>1.79</td>
<td>7 Sensible heat of air draft for coal grinding</td>
<td>27.59</td>
<td>1.79</td>
</tr>
<tr>
<td>8 Sensible heat of fly ashes in air draft for coal grinding</td>
<td>0.41</td>
<td>0.01</td>
<td>8 Sensible heat of fly ashes in air draft for coal grinding</td>
<td>0.41</td>
<td>0.01</td>
</tr>
<tr>
<td>9 Other heat expenditures</td>
<td>−77.9</td>
<td>−5.07</td>
<td>9 Other heat expenditures</td>
<td>−77.9</td>
<td>−5.07</td>
</tr>
<tr>
<td>10 Total thermal energy input</td>
<td>1538.81</td>
<td>100%</td>
<td>10 Total thermal energy output</td>
<td>1538.81</td>
<td>100%</td>
</tr>
</tbody>
</table>

Total energy recovery efficiency: 69.5%
References