Exergy Analysis of Metallurgical-grade Silicon in Vacuum Induction Refining Process

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Abstract. Combination of electric and thermal calculation method based on the principle of induction heating, the exergy analysis had been done, the results show that the effective exergy account for 38.52%, unavailable electric energy accounted for 26.36% of total exergy loss, and the exergy loss induced by heat dissipation is 69.51%. The average exergy efficiency from 361s to 960s is higher than the other two stages and especially the exergy efficiency of 961s to 1800s is less than 14%. The exergy loss accounted for a large proportion is caused by the heat dissipation. Therefore, reducing the exergy loss of heat dissipation is the most important way to optimization of vacuum induction refining process.

1. Introduction
Energy conservation and improve energy efficiency is the way to protect and improve the environment. Currently, promoting economic and social coordinated and sustainable development is a strategic task for the international community. In modern clean refining process, induction heating is widely applied to produce the required thermal power in several heating and refining systems [1-3]. The main advantages of using induction heating process when compared to any other heating process are its fast heating rate, good reproducibility and low energy consumption [2,3]. Vacuum induction refining (VIR) of industrial silicon applied to when use the way of metallurgical to produce multi-crystalline silicon, not only has the advantages of induction heating, and combined with the benefits of vacuum condition, which can purify industrial silicon initially [4].

In this paper, a detailed exergy analysis of the vacuum induction refining of MG-Si has been presented. In the previous study, attention was paid to the energy efficiency and energy conversion of steelmaking or thermal treatment by induction heating process[5-7,10], and few people concerned about the process of induction refining of the industrial silicon. But in the analysis presented here, which not only details the vacuum induction refining process of industrial silicon, also use exergy method to calculation and evaluation during the energy conversion of VIR process based on a large number of experimental data. The present paper is expected to fill the gap, and laid the foundation for future optimization.
2. Exergy analysis of industrial silicon by VIR process

2.1. The vacuum induction refining process

The geometry of structure and configuration of a small induction heating furnace for producing multicrystalline silicon is shown in Fig. 1.

![Fig. 1 Schematic of the vacuum induction refining furnace](image)

Powdered MG-silicon material is loaded into the graphite crucible, through the role of the vacuum pump, the vacuum refining furnace is pumped to a vacuum degree, and has been maintained. Heat the silicon material until it melted by induction heating system. The whole process, according to the temperature variations of the silicon material, we found the heating can be divided into three stages by a large number of experiments, namely, the heating slower stage (preheating stage), the heating faster stage (rapid heating stage), the temperature remained unchanged stage (constant temperature stage). The results are shown in Table 1.

| Stages               | Time     | Load electrical parameters (U*A) |
|----------------------|----------|----------------------------------|
| Preheating stage     | 0~360s   | 97.2*88w                         |
| Rapid heating stage  | 361~960s | 225*135 w                        |
| Constant temperature stage | 961~1800s | 175*78w                         |

The temperature variations of silicon material in the furnace heating process are shown in Fig. 2.
The actual vacuum induction refining process is thermoelectric coupling process, very complex. To be able to carry out the analysis and calculation of exergy, made the following assumptions:

1. In vacuum environment, the convective heat transfer is ignored.
2. Silicon materials in the solid or liquid, the specific heat capacity is not vary with temperature changes.
3. Ignore the chemical reaction is caused by impurities of silicon material.
4. Ignore the formation heat of silicon material electromagnetic induction.
5. The heat transfer process is steady-state heat transfer.

2.2. Exergy analysis procedure

The exergy analysis procedure is shown in Fig.3. In vacuum induction refining process, the main input is electric energy, all of the exergy; the main outputs are heating silicon to melt and the molten silicon, the loss of various parts, heat dissipation include cooling water, furnace radiating heat, flue gas heat away etc. Based on the analysis, every input and output exergy is calculated including energy input and output, lastly, exergy efficiency is calculated.

![Figure 2: Process temperature for industrial silicon heating](image)

![Figure 3: Exergy flow chart of the VIR process](image)

The exergy balance can be expressed as the following formula:

$$\sum E_{in} = \sum E_{out} + \sum \Delta E_x$$  \hspace{1cm} (1)

Where $E_{in}$ is the income exergy, for our study system, $E_{in}$ is the electric exergy; $E_{out}$ is the exergy expenditure after the end of whole process; $E_x$ is the amount of change of the system exergy. To whole
process of the system is divided into three stages, that is the amount of change of the system exergy is consist of three parts, each part include $E_{\text{usable}}$ and $E_{\text{loss}}$ (the usable and loss of exergy throughout the each stage ).

The purpose of vacuum induction refining process of the silicon material, is the rapid heating silicon material to melt and impurities volatilization under the action of vacuum, so according to exergy efficiency $\eta = \left( \frac{\sum E_{\text{usable}}}{\sum E_{\text{in}}} \right) \times 100\%$, the exergy efficiency can be calculated as 38.52%. The exergy distribution of the VIR process is shown in Fig.4.

![Fig. 4 Exergy distribution of the VIR process](image)

In VIR process, heat is supplied by the transmission effect. During the transfer process, unavoidable existence exergy losses namely internal exergy loss. Internal exergy loss is caused by the irreversibility of the process, is essentially of the energy devaluation. It is induced by transformation of electric energy to heat energy and heat transfer from higher temperature zone to lower temperature zone, and electromagnetic induction process, silicon material endothermic process, graphite crucible heat transfer process and so on, among these process, along with internal exergy losses, accounting for about 24.1% of ineffective exergy. Thus, it can be seen, the internal loss is only part of the entire process exergy loss for the system of our study, and the total exergy loss equal to the ineffective exergy, namely

$$\sum E_{\text{loss}} = \sum E_{\text{ineffective}}$$

(2)

The exergy loss composition and comparison of VIR process is shown in Fig.5.
Fig. 5 The exergy loss composition and comparison of VIR process

According to the results of the calculations, combined with Fig.5, in VIR process, the exergy loss is mainly concentrated in the external loss, which accounted for a large proportion of the exergy loss. External exergy loss includes unavailable electric exergy, and a considerable portion of the heat transfer exergy loss, as same as improve the electrical exergy efficiency, the external exergy loss can be adjusting the system parameters, improve devices to perform control and reduction. But this is only one hand, for the system, internal exergy loss also can affect external exergy loss, as the external exergy loss can have intensified internal exergy loss. Such as the exergy of cooling water and flue gas (maintain the vacuum siphoned gas) taken away is affected by heat radiation and conduction. The more heat exergy dissipation, the more obviously the temperature rise of the furnace, eventually leading to the result is the exergy loss of taken away by the cooling water and flue gas increased. So a very important aspect of reduce internal and external exergy loss is to reduce the exergy loss in the heat transfer process. However, the exergy loss of heat dissipation is inevitable, and it is difficult to be reduced, as long as the temperature of heated body is higher than the environment, it will inevitably along with heat transfer, is more prominent in a vacuum environment. Necessarily, the above electrical energy parameters is also impact factor of the exergy amount of furnace flue gas and cooling water. But compare with the heat dissipation exergy loss, the impact of electrical energy parameters is relatively small. Exactly as Fig.5 shown, the heat transfer exergy loss is the maximum expenditure of the exergy losses. In VIR system, we can through the use of better insulation materials to reduce the thermal exergy consumption, but to fundamentally solve the problem of heat dissipation; it needs more comprehensive and in-depth analysis of this system. Therefore, according to the stage division of the system, each stage of the system exergy efficiency are analyzed and discussed. The distributions of each stage exergy efficiency in the different time are shown in Fig.6.
The distributions of each stage exergy efficiency in the different time

Depending on the exergy efficiency of the calculation results, we have come to the average of the exergy efficiency of each stage, and the results are shown in Fig. 7

The average exergy efficiency of the various stages

The exergy values input to each stage are also different due to the different control parameters. But it is certain that the input value of exergy first heated graphite crucible, before the heat transfer of the crucible to the silicon material. The study system is the silicon material which absorb heat from the graphite crucible. Fig.6 is mainly express the system exergy efficiency under the heat transfer action. From Fig.7, it can be seen, exergy efficiency can be increased to a higher position at the ending of stage 1 and stage 2, while tail end of stage 2, exergy efficiency quickly reduces, until the stage 3, exergy efficiency has been maintained at a lower level.

From Fig.7, it was concluded that the average exergy efficiency of stage 2 is higher, the stage 1 and stage 3 average exergy efficiency is relatively lower, and especially the exergy efficiency of stage 3 is less than 14%. Conjunction with Fig.6, Fig.7, and the formula (26).

\[ \delta E_L = T_0 \left( \frac{T_H - T_L}{T_L T_H} \right) \delta Q \]  

Have a comprehensive analysis to obtain the answer: The exergy loss in the heat transfer process is affected by the temperature difference of heat transfer and quantity of heat. A larger temperature difference of the heat transfer can be made exergy loss increases, resulting in exergy efficiency reduce. Therefore, in the beginning of stage 1, exergy efficiency is lower, with the narrowing of the difference in temperature, exergy loss is also gradually reduced, and exergy efficiency is correspondingly increased. The reason why exergy efficiency of stage 2 appeared fluctuation is because in the
beginning of stage 2, the control parameters have changed, the temperature of the graphite crucible soon rise, widening the difference in temperature between the crucible and silicon material, so the exergy efficiency declined firstly, subsequently, same as the stage 1, the efficiency starts to rise, to around 848s, the silicon temperature reaches the melting point, and it began to absorb the latent heat, the equivalent of no temperature difference heat transfer, the exergy efficiency is highest, but with the end of this process, the exergy efficiency begins to lower, silicon material is completely melted, although the temperature difference between crucible and silicon material is very small, but due to the sharp reduction of the heat absorption, and also makes the exergy efficiency is maintained at a lower level, and this is the stage 3, most exergy were consumed by the furnace, used for cooling system, in other words, the waste exergy of this stage is the greatest, but this stage is the most important refining process, and the objective is preliminary purification and stirring action of MG-Si. If only standing energy utilization point of view, I do not recommend this stage, or reduce the time of this stage, to improve exergy efficiency, benefit for energy conservation.

3. Conclusion
Following conclusions can be made based on this study:

(1) Combination of electric and thermal calculation method based on the principle of induction heating, most of the exergy analysis of MG-Si in vacuum induction refining process that had been done, the results show that the effective exergy account for 38.52%, unavailable electric energy accounted for 26.36% of total exergy loss, Exergy loss induced by heat dissipation is 69.51% of total exergy loss.

(2) Compared with external loss, internal losses is relatively small caused by irreversibility, in external losses, the exergy loss accounted for a large proportion is caused by the heat dissipation. Therefore, reducing the exergy loss of heat dissipation is the most important way to optimization of vacuum induction refining process. This requires the process to choose a good parameter of the electric equipment, apply advanced materials, enhanced insulation and reduce exergy consumption.

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