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STUDY OF THE MECHANISM OF CINDER LEACHING PROCESS WITH HYDROCHLORIC ACID

Ochilov E.A., Toshpulatova G.R.,
Toshpulatova G.R.., Khushvaktova U.A.,
Khamdamov D.Kh., Kamolov T.O., Yuldashev O.R.
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Abstract. The paper presents the results of a comprehensive study of the process of cinder leaching with hydrochloric acid in order to determine the patterns of transition of target components from the solid phase into solution and to establish optimal technological parameters of the process. Particular attention is paid to studying the influence of hydrochloric acid concentration, temperature, and duration of processing on the leaching efficiency, the degree of recovery of useful components, and the completeness of chemical reactions. The effect of hydrochloric acid concentration on the cinder leaching process is examined. Changing the reagent concentration has a significant effect on the rate of interaction between the acid and the components of the solid material, the solubility of the corresponding compounds, and the degree of transition of target elements into the liquid phase. At an insufficient acid concentration, chemical interaction may proceed incompletely, which leads to a decrease in the degree of recovery of useful components. Increasing the reagent concentration, as a rule, contributes to the intensification of the process due to an increase in the number of active hydrogen ions in solution. At the same time, an excessive increase in acid concentration does not always provide a proportional increase in recovery, since the result depends on the mineral and chemical composition of the cinder, the nature of the compounds contained in it, and the characteristics of their interaction with the reagent. Therefore, determining a rational concentration of hydrochloric acid is of great importance for ensuring efficient reagent utilization and reducing operational costs.

Keywords: leaching, cinder, hydrochloric acid, hydrometallurgy, non-ferrous metals, recovery rate, process kinetics, temperature, acid concentration, liquid-to-solid ratio.

Introduction

The coal industry remains a crucial sector of global energy, despite the active development of alternative energy sources. The combustion of coal generates significant volumes of fly ash and slag waste, the accumulation of which creates environmental problems. However, modern research increasingly considers coal ash not as waste, but as a promising secondary mineral raw material for the extraction of valuable and rare metals [1, 2].

Coal ash contains a wide range of compounds: oxides of silicon, aluminum, calcium, iron, as well as impurities of rare earth elements (REE), germanium, gallium, scandium, vanadium, etc.

In developed countries (USA, China, Russia, EU countries), research is actively underway to involve ash in processing. The main technologies include: acid and alkaline leaching, the use of plasma and thermochemical methods, flotation, and hydrometallurgical schemes for comprehensive extraction. Industrial use of ash is currently limited mainly to the production of construction materials (cement, concrete, ceramics), whereas metallurgical utilization is at the stage of laboratory and pilot research [3].

The object of the study is the cinder obtained as a result of roasting metal-containing concentrate.

The aim of the work is to investigate the current state and development prospects of the coal industry with an emphasis on the use of coal ash as a complex secondary raw material, to determine the possibilities and directions for extracting valuable and rare metals from it, and to substantiate the scientific, technical, and environmental benefits of involving coal slag waste in processing.

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Results and Discussion

Leaching is one of the main hydrometallurgical methods for processing metal-containing waste and intermediate products of metallurgical production. This process is based on the selective transfer of target components from the solid phase into solution under the action of chemical reagents. The use of hydrochloric acid as a leaching agent is due to its high reactivity towards a number of metal oxides and other compounds, which increases their degree of dissolution and creates prerequisites for subsequent separation, concentration, and purification of target components. Studying the kinetic and physicochemical patterns of acid leaching of cinders allows establishing the influence of the main technological parameters on process efficiency and determining optimal conditions for extracting valuable metals [4].

Preliminary determination of the elemental and oxide composition of the initial material was carried out by X-ray fluorescence analysis (XRF). Experimental studies were conducted with systematic variation of the main technological parameters: hydrochloric acid concentration in the range of 1–6 mol/L, process temperature within 25–90 °C, and leaching duration from 15 to 180 min. To evaluate the effect of hydrodynamic and mass transfer conditions on the degree of transition of components into solution, the solid-to-liquid ratio (S:L) was varied from 1:10 to 1:50. This approach made it possible to comprehensively study the effect of leaching reagent concentration, temperature, phase contact duration, and liquid phase flow rate on the efficiency of acid leaching of cinder.

Taking into account the established phase composition of the cinder, the mechanism of its leaching process with hydrochloric acid can be represented by the following reactions [5]:

$Ca_2Al(SiAl)O_7 + 10HCl = 2AlCl_3 + SiO_2 + 2CaCl_2 + 5H_2O$ (1)

$CaAl_2Si_2O_8 + 8HCl = 2AlCl_3 + 2SiO_2 + CaCl_2 + 4H_2O$ (2)

$CaSiO_3 + 2HCl = SiO_2 + CaCl_2 + H_2O$ (3)

$Fe_2O_3 + 6HCl = 2FeCl_3 + 3H_2O$ (4)

$Cu_2O + 2HCl = 2CuCl + H_2O$ (5)

$NiO + 2HCl = NiCl_2 + H_2O$ (6)

$ZnO + 2HCl = ZnCl_2 + H_2O$ (7)

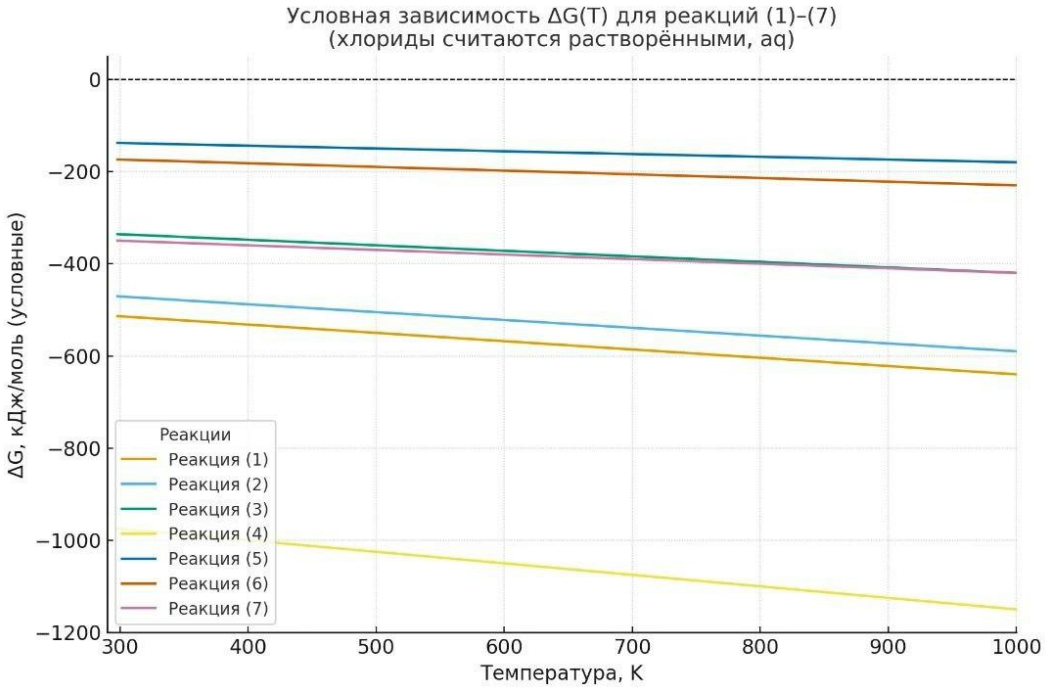

Fig. 1. Dependence of Gibbs free energy on temperature for reactions (1) - (7)

It can be seen that the probability of reactions between gehlenite and anorthite with hydrochloric acid in the temperature range of 298–373 K, which ensure the transfer of aluminum into solution in the form of its chloride, is practically impossible due to the positive values of Gibbs free energy for reactions (1) and (2). At the same time, there is a high probability of wollastonite decomposition by hydrochloric acid according to reaction (3) with the formation of calcium chloride and quartz. The formation of a free amount of $CaCl_2$ is not fundamental, since it is recycled back to the head of the technology—to the ash roasting process.

High negative values of Gibbs free energy for reactions (4)–(7) indicate the possibility of transferring iron and non-ferrous metals as their chlorides into solution. The established patterns show that according to thermodynamic calculations, the transfer of aluminum into solution from its easily soluble compounds (gehlenite, anorthite) by leaching cinder with hydrochloric acid is not possible. At the same time, the results of experimental studies on cinder leaching given below fully confirm the possibility of high aluminum extraction into solution from cinder [4, 5, 6].

Experimental data showed that:

- Increasing the HCl concentration to 4–5 mol/L promotes an increase in the recovery rate of iron, copper, and zinc; however, a further increase in concentration has no significant effect.
- Increasing the temperature accelerates process kinetics: at 25 °C, copper extraction was ~45%, whereas at 80 °C it reached 85–90%.
- Leaching time also plays a key role: the highest rate of metal transition into solution is observed in the first 60 minutes, after which the process slows down, which is associated with passivation of the solid phase surface.
- The optimal S:L ratio is 1:20–1:30, ensuring a high level of metal extraction with minimal reagent losses.

Thus, coal power plant ash is not only a byproduct, but also a promising complex raw material for the metallurgy of the future. Modern research and innovative technologies make it possible to consider it as a source of strategically important elements. In the coming decades, active development of directions related to the deep processing of ash can be expected, which will simultaneously solve the environmental and raw material problems of the coal industry.

Conclusion

As a result of the study, the main patterns of the cinder leaching process with hydrochloric acid were established, and rational technological parameters ensuring efficient extraction of target components from solid raw materials into solution were determined. It is shown that process efficiency significantly depends on hydrochloric acid concentration, temperature, processing duration, and the solid-to-liquid ratio.

It was established that the most efficient process flow is achieved at a hydrochloric acid concentration of 4–5 mol/L, temperature of 70–80 °C, processing duration of 60–90 minutes, and a solid-to-liquid (S:L) ratio of 1:20 to 1:30. The selection of these parameters allows creating favorable conditions for the interaction of the acid reagent with cinder components, accelerating the dissolution of acid-soluble compounds, and increasing the completeness of target elements' transition into the liquid phase.

The influence of hydrochloric acid concentration is due to its active participation in chemical dissolution reactions of cinder components. When using a solution with an insufficient concentration, incomplete interaction of the reagent with the solid phase is possible, which limits the extraction degree of useful components. Increasing acid concentration to the established range contributes to process intensification. However, further concentration increase is not always economically viable, as it can lead to higher reagent consumption without a proportional increase in leaching efficiency.

The temperature mode of 70–80 °C accelerates chemical reactions and improves mass transfer conditions between solid and liquid phases. A processing duration of 60–90 minutes provides necessary time for reagent interaction with components available for dissolution. Maintaining the S:L ratio within 1:20–1:30 ensures a sufficient amount of liquid phase for the process and effective transfer of soluble compounds into solution.

The practical significance of the results lies in the possibility of their utilization in developing and improving technological schemes for hydrometallurgical processing of metal-containing cinders. Application of the established parameters can contribute to increasing recovery rates of valuable components, rational use of hydrochloric acid, reducing duration of technological operations, and lowering unit costs of raw material processing.

Thus, the research results confirm the prospects of using hydrochloric acid leaching for processing metal-containing cinders. The identified technological parameters can be used as initial conditions for further laboratory and pilot-plant tests aimed at increasing process efficiency and developing an economically sound technology for extracting valuable components from secondary mineral raw materials. In transitioning to an industrial scale, it is necessary to additionally evaluate the material balance of the process, acid consumption, solution composition, corrosion resistance of equipment, and possibilities for subsequent recovery of target metals.

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