MRI Characterization of the Pore Structure Evolution by Forced Aeration during Heap Leaching

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Abstract. In spite of lots of methods in improving the performance of heap leaching, much controversy on the industrial applications remain. A relatively new and effective idea of introducing aeration to heap leaching, especially in abiotic heap leaching, may be a better way. Experiments on water content (WC) of the leaching columns employing a novel heap leaching apparatus and Magnetic Resonance Imaging (MRI) by changing aeration intensity (AI) were conducted. The results show that WC within the heap can be effectively increased which may enlarge the area of liquid-solid interface to probably improve the leaching efficiency and performance.

Keywords: Heap Leaching, Water Content (WC), MRI, Aeration Intensity (AI), Leaching Efficiency

1 Introduction

Heap leaching is a simple hydrometallurgical extraction technique commonly employed in recovering valuable metals from low-grade or refractory ores [1]. With comparably low operational costs and simplicity, short construction time, high recovery rate and environmental benefits, it has become more popular in the ore processing [2]. An ore leaching heap is a porous medium constituted of irregular ore particles with different shapes and sizes [3]. So, there exists bulk of complicated pore structures and uncertain liquid flowing channels within the heap.

There are many methods in increasing the leaching performance such as presenting stress wave, loosening the dump, introducing external electric field [4], etc. Currently, a new and better idea of introducing forced aeration in the abiotic heap leaching is proposed to improve the leaching efficiency of the heap [5]. J.A. Brierley et al [6] believed that whether aeration should be utilized in the abiotic heap leaching has become a key problem restricting the development of leaching mining. Consequently, it is of significance for guiding the construction of a leaching heap to clearly understand
the evolutionary processes of granular structure and the enhanced leaching mechanism by forced aeration. Despite the achievements of black box theory, analog simulation and X-ray CT [7] in studying the flow behavior of leaching solution within the heap system, there are deficiencies such as low accuracy and obscure gas-liquid differentiation. Recently, Magnetic Resonance Imaging (MRI), as a non-destructive imaging technique, has been preliminarily utilized in research fields of physical mechanics and fluid mechanics [8]. The aim of this paper is to fully understand the effect of different aeration intensity (AI) on water content (WC) of the system. In order to reveal the effect, laboratory experiments are conducted.

2 Experimental

2.1 Materials
As shown in Table 1, the samples, obtained from the leaching heap of a copper mine, were dried, screened for 30 minutes, weighted and grouped into particles with different sizes.

| Size (mm) | Weight (%) |
|-----------|------------|
| <0.7      | 19.1       |
| 0.7~2.5   | 11.3       |
| 2.5~5.5   | 19.6       |
| 5.5~9.5   | 19.8       |
| 9.5~13.5  | 20.6       |
| 13.5~25.0 | 9.6        |

2.2 Experimental Apparatus
Firstly, a novel heap leaching apparatus schematically depicted in Fig. 1 was utilized to conduct the column leaching experiments as AI changed. This apparatus was mainly consisted by the leaching columns (fabricated by plexiglass), solid-liquid-gas circulation system. The maximum AI of the apparatus was 0.5 m³·h⁻¹.

MRI system (1.5T Signa HDxt) based on T1 FLAIR acquisition sequence was employed to perform the column imaging [9].

2.3 Preparation and Operation
In order to eliminate the influence of chemical actions [10], purified water was employed to be leaching solution for this experiment. The specific experimental processes were as follows:
a) According to Table 1, agar balls were fabricated, well stirred, packed into columns S1 to S3 of the novel column leaching apparatus and named A, B and C respectively. All the specimens were saturated for 24 hours to remove air within them.

b) Air was pumped into the three specimens, AI of which were 0, 0.3 m³·h⁻¹ and 0.5 m³·h⁻¹ accordingly.

c) A, B and C were fixed in clamping devices to reduce the vibration effects on MRI images, and then they were successively put into the MRI system for imaging experiments. During experiments, the field of view was approximately 150 mm × 150 mm in the x and y directions, and thickness and notch size of the slice was 4 mm and 0.4 mm, respectively. It used a total repetition time of 1820 ms, an echo time of 29.3 ms and an inversion time of 810 ms.

3 Results and Discussion

The 2D MRI images acquired from A, B, C and the corresponding velocity field distributions of water were presented. Obvious differences occurred in the distribution of solution as AI changed.Appearances of solution in all the images were disordered and inhomogeneous, and flowrate in the central region and boundary was faster, however, solution within B (Fig. 3) and C (Fig. 4) spread wider and more disordered than that in A (Fig. 2).

![Fig 2. Comparison of the liquid distribution when AI was 0](image)

![Fig 3. Comparison of the liquid distribution when AI was 0.3 m³·h⁻¹](image)

![Fig 4. Comparison of the liquid distribution when AI was 0.5 m³·h⁻¹](image)

MRI images of the three specimens were pretreatmented, then, sections of the object regions were obtained, within which the cross section was 150 pixels × 150 pixels and the longitudinal section was 285 pixels × 117 pixels in the x and y directions. Afterwards, the binary flowing images combined with liquid and solid were obtained based upon a certain threshold [11]. Taking C as an example, as presented in Fig. 5, the MRI and binary flowing images of the cross section and longitudinal section were obtained, the white and black of which represented solution and ore particles respectively.
As shown in Fig. 6, the 2D images of C were imported in MATLAB using a 3D stereogram analysis of the signals measured in pixel. The peak load occurred in the intermediate regions of the two sections, and solution in B and C was more widespread than that in A.

Fig 5. Image processing of C

As shown in Fig. 6, the 2D images of C were imported in MATLAB using a 3D stereogram analysis of the signals measured in pixel. The peak load occurred in the intermediate regions of the two sections, and solution in B and C was more widespread than that in A.

Fig 6. 3D diagrams of WCT. (a) cross and (b) longitudinal sections

A concept of WC of MRI images was introduced to scientifically analyze the effect of AI on heap leaching, calculated by [12]

\[
\varphi = \frac{1}{n} \sum_{i=1}^{n} \varphi_i 
\]

(1)

Where \( n \) was the number of statistical areas within MRI images. \( \varphi_i \) was WC of region \( i \).

As shown in Fig. 5, the binary flowing images were cut in longitudinal pixels, proportion of the white part of which could be approximately seen as WC of this region. Thus

\[
\varphi_i = \frac{S_{i,W}}{S_{i,T}} \quad (i=1,2,3,\ldots,110) 
\]

(2)

Where \( S_{i,W} \) represented water area in region \( i \). \( S_{i,T} \) was pixel area of region \( i \).

WC of different regions in the binary flowing images of A, B and C, taking A as an example, was calculated and analyzed by ORIGIN depicted in Fig. 7.
By effective calculation, WC of A could be calculated exactly as:

\[
\begin{align*}
\phi_A &= \frac{S_1}{S_2} \sum_{i=1}^{110} \phi_i \times 100\% / 110 \\
\phi_{A'} &= \sum_{i=1}^{117} \phi_i \times 100\% / 117
\end{align*}
\] (3)

Where \(\phi_A\) and \(\phi_{A'}\) were WC of the cross section and longitudinal section of A. \(S_1\) was the effective pixel area of water in the image, and \(S_2\) represented the total pixel area of the image. By calculation, WC of A (\(\phi_A\) and \(\phi_{A'}\)), B (\(\phi_B\) and \(\phi_{B'}\)) and C (\(\phi_C\) and \(\phi_{C'}\)) MRI images were given in Table 2.

**Table 2.** WC analysis of A, B and C MRI images

|     | A (%) | B (%) | C (%) |
|-----|-------|-------|-------|
| \(\phi_A\) | 22.76 | 34.28 | 51.12 |
| \(\phi_{A'}\) | 27.55 | 37.99 | 41.66 |

It could be seen \(\phi_A < \phi_B < \phi_C\) and \(\phi_{A'} < \phi_{B'} < \phi_{C'}\) indicating that aeration was beneficial to the increase of WC. It indicated that the aerated heap leaching system would accommodate more solution thus to improve liquid-solid interfacial area then to increase the leaching efficiency.

**4. Conclusions**

Column leaching experiment and MRI characterization of seepage property of water within the specimens as AI changed were conducted. The 2D acquisitions of MRI images from the three specimens showed that WC of which was obviously promoted by aeration especially when the AI was 0.5 m³·h⁻¹. It indicated that aeration could improve the area of liquid-solid interface, a favorable result as more ore particles within the heap were possibly contacted with the leaching solution to probably improve the heap leaching performance.

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