Notice

DESCRIPTION CN120619034A

A method for removing heavy metals from fly ash from waste incineration using flash Joule heating technology

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基于闪蒸焦耳加热技术去除垃圾焚烧飞灰中重金属的方法

[0001]

Technical Field

技术领域

[n0001]

This application relates to the field of waste treatment technology, and in particular to a method for removing heavy metals from fly ash from waste incineration based on flash evaporation Joule heating technology.

本申请涉及垃圾处理技术领域，尤其涉及一种基于闪蒸焦耳加热技术去除垃圾焚烧飞灰中重金属的方法。

[0003]

Background Technology

背景技术

[n0002]

With the continuous acceleration of urbanization, waste incineration, as the main method of final disposal of municipal solid waste, has played an important role in achieving waste reduction, harmlessness and energy utilization.

随着城市化进程的不断加快，垃圾焚烧作为主要的生活垃圾终端处置方式，在实现垃圾减量化、无害化和能源化利用方面发挥了重要作用。

However, the fly ash produced during waste incineration is enriched with large amounts of heavy metals (such as Pb, Zn, Cd, Cu, etc.) and harmful substances such as dioxins, and is listed as hazardous waste in the National Hazardous Waste List, which urgently needs to be disposed of safely, efficiently and economically.

然而，垃圾焚烧过程中产生的飞灰由于富集了大量的重金属(如Pb、Zn、Cd、Cu等)及二噁英等有害物质，被《国家危险废物名录》列为危险废物，亟需进行安全、高效、经济的处置。

Existing fly ash treatment technologies include cement solidification, chemical stabilization, hydrothermal treatment, and high-temperature melting. However, these methods generally suffer from technical bottlenecks such as high treatment costs, high energy consumption, low resource recovery efficiency, and high risk of secondary pollution, making it difficult to meet the current practical needs for the coordinated development of fly ash harmlessness and resource utilization.

现有飞灰处理技术包括水泥固化、化学稳定、水热处理及高温熔融等，但这些方法普遍存在处理成本高、能耗大、资源回收效率低和二次污染风险高等技术瓶颈，难以满足当前飞灰无害化与资源化协同发展的实际需求。

[n0003]

Existing technologies for treating fly ash from waste incineration mainly include traditional cement solidification and chemical stabilization methods and hydrothermal treatment. Both of these methods suffer from problems such as low treatment efficiency, incomplete removal of heavy metals, difficulty in resource recycling, and high energy consumption.

现有技术在垃圾焚烧飞灰处理方法主要包括传统的水泥固化与化学稳定化方法和水热处理，这两种方式在处理过程中存在处理效率低、重金属去除不彻底、资源回收难度大以及工艺能耗高等问题。

Specifically, traditional cement solidification and chemical stabilization methods mainly reduce environmental risks by passivating and burying heavy metals in fly ash, but they cannot truly remove heavy metals, and the treated material still needs to be safely landfilled, posing long-term environmental hazards.

具体的，传统的水泥固化与化学稳定化方法主要通过将飞灰中重金属钝化、包埋来降低其环境风险，但无法真正实现重金属的脱除，且处理后仍需安全填埋，存在长期的环境隐患。

Although hydrothermal treatment technology can change the morphological distribution of heavy metals, it has limitations such as long processing cycles, complex equipment, and difficulty in scaling up. While high-temperature melting technology can achieve relatively thorough stabilization of heavy metals, it has high requirements for equipment materials, high energy consumption, and high operating costs. Furthermore, under high-temperature conditions, it is prone to causing chlorine volatilization of heavy metals and abnormal enrichment of elements such as Cu, resulting in secondary pollution and resource waste. In addition, existing heat treatment processes generally rely on traditional heating methods, which have slow heating rates and large heat losses, making it difficult to achieve rapid, efficient, and synergistic removal of various heavy metals from fly ash, thus restricting the improvement of fly ash resource utilization.

水热处理技术虽然能改变重金属的形态分布，但存在处理周期长、设备复杂、难以规模化等限制。而高温熔融技术虽然能够实现重金属较彻底的稳定化，但对设备材质要求高，能耗大、运行成本高，且在高温条件下易引发重金属的氯促挥发和Cu等元素的异常富集，造成二次污染和资源浪费。 此外，现有热处理工艺普遍依赖传统加热方式，升温速率慢、热损失大，难以实现对飞灰中多种重金属的快速、高效、协同脱除，制约了飞灰资源化利用水平的提升。

[0006]

Summary of the Invention

发明内容

[n0004]

The present invention aims to solve one of the problems existing in the background art.

本发明旨在解决背景技术中存在的问题之一。

[n0005]

Therefore, this invention provides a method for removing heavy metals from waste incineration fly ash based on flash evaporation Joule heating technology. This method has the advantages of compact structure, rapid processing and high removal efficiency, and is suitable for the harmless disposal and resource recycling of waste incineration fly ash.

为此，本发明提供一种基于闪蒸焦耳加热技术去除垃圾焚烧飞灰中重金属的方法，该方法具备结构紧凑、处理快速、脱除效率高等优势，适用于垃圾焚烧飞灰的无害化处置和资源化回收。

[n0006]

The technical solution adopted by this invention to solve its technical problem is:

本发明解决其技术问题所采用的技术方案是：

[n0007]

A method for removing heavy metals from waste incineration fly ash based on flash Joule heating technology includes the following steps:

一种基于闪蒸焦耳加热技术去除垃圾焚烧飞灰中重金属的方法，包括以下步骤，

[n0008]

Step 1: Mix the fly ash from waste incineration with the conductive heat-generating material until a mixture is obtained;

步骤一，将垃圾焚烧飞灰与导电助热材料混合均匀，得到混合料；

[n0009]

Step 2: The mixture is subjected to flash joule heat treatment, cooled, and the resulting waste incineration fly ash residue is obtained.

步骤二，将所述混合料进行闪蒸焦耳热处理，冷却并得到垃圾焚烧飞灰残渣。

[n0010]

Furthermore, the conductive heat-generating material is selected from one or more combinations of carbon black, graphite, activated carbon, and coke powder.

进一步地，所述导电助热材料选自炭黑、石墨、活性炭、焦粉中的一种或多种的组合。

[n0011]

Furthermore, the mass ratio of waste incineration fly ash to conductive heat-generating material in the mixture is 20:1 to 1:1.

进一步地，所述混合料中垃圾焚烧飞灰与导电助热材料的质量比为20:1～1:1。

[n0012]

Furthermore, the fly ash needs to be dried and ground before being mixed with the conductive heat-generating material, and the particle size of the fly ash is less than or equal to 100 mesh.

进一步地，所述飞灰在与导电助热材料混合前，需要进行干燥和研磨，所述飞灰的粒径小于等于100目。

[n0013]

Furthermore, prior to step two, the mixture is pretreated to change its resistance to ≤3Ω.

进一步地，在所述步骤二前，对混合料进行预处理，改变混合料的电阻至≤3Ω。

[n0014]

Furthermore, the pretreatment method of the mixture is as follows: the mixture is placed in a quartz tube and connected to the Joule flash evaporation experimental platform. The mixture sample in the quartz tube is compacted. Then, the quartz tube is placed on the flash Joule heating device, and the degree of compression of the sample is adjusted until the resistance is basically stable. The mixture sample is pretreated by low-voltage pulse.

进一步地，所述混合料预处理的方式为：将混合料放入石英管中，连接至焦耳热闪蒸实验平台，将石英管内的混合料样品压实，然后将石英管放在闪焦耳加热设备上，调节样品的压缩程度，直至电阻基本稳定，通过低压脉冲对混合料样品进行预处理。

[n0015]

Furthermore, the parameters for the low-voltage pulse preprocessing are set as follows: discharge voltage 30-100V, single discharge time 0.1-1s, time interval 0.1-1s, and flash evaporation 1-3 times.

进一步地，所述低压脉冲预处理的参数设置为：放电电压30～100V，单次放电时间0.1～1s，时间间隔为0.1～1s，闪蒸次数1～3次。

[n0016]

Furthermore, the parameters of the flash Joule heat treatment are set as follows: discharge voltage 80-380V, single discharge time 0.1-1s, time interval 0.5-2s, and flash number 1-5 times.

进一步地，所述闪蒸焦耳热处理的参数设置为：放电电压80～380V，单次放电时间0.1～1s，时间间隔为0.5～2s，闪蒸次数1～5次。

[n0017]

The beneficial effects of this invention are that it applies flash evaporation Joule heating technology to the rapid removal of heavy metals from waste incineration fly ash. By mixing fly ash with conductive heat-generating materials (such as carbon black, graphite, activated carbon, etc.) and setting its resistance ⩽3Ω as the treatment condition, it achieves high-temperature treatment in seconds, which significantly promotes the transformation and efficient volatilization of heavy metals such as Pb, Zn, and Cd.

本发明的有益效果是，本申请将闪蒸焦耳加热技术应用于垃圾焚烧飞灰中重金属的快速脱除，通过飞灰与导电助热材料(如炭黑、石墨、活性炭等)混合，并设定其电阻≤3Ω作为处理条件，实现秒级高温处理，显著促进Pb、Zn、Cd等重金属的形态转化和高效挥发。

This technology modulates the electrical properties of the mixture through low-pressure pulse pretreatment, and, combined with precise control of flash evaporation voltage, time, and frequency, constructs an efficient, low-consumption, and green dry fly ash heavy metal treatment path.

该技术通过低压脉冲预处理调控混合料电性，结合精确控制的闪蒸电压、时间和频次，构建了一个高效、低耗、绿色的干式飞灰重金属处理路径。

Specifically,

具体的，

[n0018]

1.

1.

This invention is based on flash Joule heating technology, which can raise the temperature of fly ash samples to 1000-3000°C in a very short time (seconds). Compared with traditional heat treatment processes, it significantly shortens the processing time, significantly reduces the overall energy consumption, avoids the energy waste and equipment heat load caused by maintaining high temperature for a long time, and improves the processing efficiency.

本发明基于闪蒸焦耳加热技术，在极短时间内(秒级)实现飞灰样品升温至1000～3000°C，相比传统热处理工艺大幅缩短处理时间，显著降低整体能耗，避免了长时间维持高温所带来的能量浪费和设备热负荷，提高了处理效率。

[n0019]

2.

2.

This invention can effectively promote the high-temperature volatilization or form transformation of heavy metals such as Pb, Zn, and Cd during flash evaporation, achieving synergistic removal. Among them, the removal rates of Zn and Cd reached 83.48% and 63.91%, respectively, under the treatment condition of 1000°C.

本发明能够在闪蒸过程中有效促使Pb、Zn、Cd等重金属实现高温挥发或形态转化，实现协同脱除，其中Zn和Cd在1000°C处理条件下脱除率分别达83.48%和63.91%。

It exhibits good simultaneous processing capability for various heavy metals under different temperature conditions, and has strong adaptability and controllability.

不同温度条件下对多种重金属表现出良好的同步处理能力，具有较强的适应性和可调控性。

[n0020]

3.

3.

Joule flash treatment significantly improves the physical structure of fly ash, promotes particle surface densification and homogenization, increases SiO2 crystallinity, and reduces chlorides and amorphous substances, providing a better physical basis for the subsequent resource utilization of fly ash (such as building material raw materials and harmless landfill), and improves the safety and stability of residues.

焦耳热闪蒸处理显著改善飞灰的物理结构，促进颗粒表面致密化与均质化，提升SiO₂结晶度、减少氯化物与非晶态物质，为后续飞灰的资源化利用(如建材原料、无害化填埋)提供了更佳的物理基础，提升了残渣的安全性和稳定性。

[n0021]

4.

4.

The flash joule heat treatment system used in this invention is an integrated charging-discharging-reaction chamber system, which occupies a small area, has a high degree of modularity, and is suitable for various processing scales and different types of fly ash samples.

本发明所采用的闪蒸焦耳热处理系统由充电-放电-反应腔一体化构成，占地小、模块化程度高，适用于多种处理规模与不同类型飞灰样品。

It is easy to operate, has a fast response time, and can be flexibly integrated into existing fly ash treatment processes, showing good prospects for engineering applications.

操作简单、响应速度快，可灵活接入现有飞灰处理流程中，具备良好的工程应用前景。

[n0022]

5.

5.

Compared with wet processes such as cement curing and hydrothermal treatment, this invention is a typical dry heat treatment process that requires no water input, avoids waste liquid treatment and equipment corrosion problems, greatly reduces environmental pollution risks and operation and maintenance costs, and improves overall environmental friendliness.

与水泥固化、水热处理等湿法工艺相比，本发明为典型的干式热处理过程，无需水资源投入，避免废液处理和设备腐蚀问题，大大降低了环境污染风险和运行维护成本，提升了整体环境友好性。

[n0023]

In summary, this invention not only achieves efficient and synergistic removal of multiple heavy metals from waste incineration fly ash, but also has the advantages of low energy consumption, strong controllability, usable residue, and low environmental burden. It breaks through many limitations of existing fly ash thermal treatment technologies and has significant environmental benefits and engineering application value.

综上所述，本发明不仅能够实现垃圾焚烧飞灰中多种重金属的高效协同去除，还兼具低能耗、可控性强、残渣可利用、环境负担小等优点，突破了现有飞灰热处理技术的诸多局限，具有显著的环境效益与工程应用价值。

[0027]

Attached Figure Description

附图说明

[n0024]

The present invention will be further described below with reference to the accompanying drawings and embodiments.

下面结合附图和实施例对本发明进一步说明。

[n0025]

Figure 1 shows the SEM+EDS images of waste incineration fly ash before and after treatment in Example 1.

图1为实施例1处理前后垃圾焚烧飞灰的SEM+EDS图。

[n0026]

Figure 2 shows the XRD patterns of fly ash from waste incineration before and after treatment in Example 1.

图2为实施例1处理前后垃圾焚烧飞灰的XRD图。

[n0027]

Figure 3 shows the particle size distribution of fly ash from waste incineration before and after treatment in Example 1.

图3为实施例1处理前后垃圾焚烧飞灰的粒径分布图。

[n0028]

Figure 4 shows the pore size distribution of fly ash from waste incineration before and after treatment in Example 1.

图4为实施例1处理前后垃圾焚烧飞灰的孔径分布图。

[n0029]

Figure 5 shows the Zn metal valence distribution of fly ash from waste incineration before and after treatment in Example 1.

图5为实施例1处理前后垃圾焚烧飞灰的Zn金属价态分布图。

[0034]

Detailed Implementation

具体实施方式

[n0030]

The invention will now be described in further detail with reference to the accompanying drawings.

现在结合附图对本发明作进一步详细的说明。

These accompanying drawings are simplified schematic diagrams, illustrating only the basic structure of the invention in a schematic manner, and therefore only show the components relevant to the invention.

这些附图均为简化的示意图，仅以示意方式说明本发明的基本结构，因此其仅显示与本发明有关的构成。

[n0031]

In the description of this invention, it should be understood that the terms "center," "longitudinal," "lateral," "length," "width," "thickness," "upper," "lower," "front," "rear," "left," "right," "vertical," "horizontal," "top," "bottom," "inner," "outer," "clockwise," "counterclockwise," "axial," "radial," and "circumferential" indicate the orientation or positional relationship based on the orientation or positional relationship shown in the accompanying drawings. They are used only for the convenience of describing this invention and simplifying the description, and are not intended to indicate or imply that the device or element referred to must have a specific orientation, or be constructed and operated in a specific orientation. Therefore, they should not be construed as limitations on this invention.

在本发明的描述中，需要理解的是，术语“中心”、“纵向”、“横向”、“长度”、“宽度”、“厚度”、“上”、“下”、“前”、“后”、“左”、“右”、“竖直”、“水平”、“顶”、“底”“内”、“外”、“顺时针”、“逆时针”、“轴向”、“径向”、“周向”等指示的方位或

位置关系为基于附图所示的方位或位置关系，仅是为了便于描述本发明和简化描述，而不是指示或暗示所指的装置或元件必须具有特定的方位、以特定的方位构造和操作，因此不能理解为对本发明的限制。

Furthermore, features specified as "first" or "second" may explicitly or implicitly include one or more of those features.

此外，限定有“第一”、“第二”的特征可以明示或者隐含地包括一个或者更多个该特征。

In the description of this invention, unless otherwise stated, "a plurality of" means two or more.

在本发明的描述中，除非另有说明，“多个”的含义是两个或两个以上。

[n0032]

In the description of this invention, it should be noted that, unless otherwise explicitly specified and limited, the terms "installation", "connection" and "linking" should be interpreted broadly. For example, they can be fixed connections, detachable connections, or integral connections; they can be mechanical connections or electrical connections; they can be direct connections or indirect connections through an intermediate medium; and they can be internal connections between two components.

在本发明的描述中，需要说明的是，除非另有明确的规定和限定，术语“安装”、“相连”、“连接”应做广义理解，例如，可以是固定连接，也可以是可拆卸连接，或一体地连接；可以是机械连接，也可以是电连接；可以是直接相连，也可以通过中间媒介间接相连，可以是两个元件内部的连通。

Those skilled in the art can understand the specific meaning of the above terms in this invention according to the specific circumstances.

对于本领域的普通技术人员而言，可以具体情况理解上述术语在本发明中的具体含义。

[n0033]

A method for removing heavy metals from waste incineration fly ash based on flash Joule heating technology includes the following steps:

一种基于闪蒸焦耳加热技术去除垃圾焚烧飞灰中重金属的方法，包括以下步骤：

[n0034]

Step 1: Mix the fly ash from waste incineration with the conductive heat-generating material evenly to obtain a mixture. The conductive heat-generating material is selected from carbon black, graphite, activated carbon, coke powder or a combination thereof, and the mass ratio of fly ash from waste incineration to conductive heat-generating material is 20:1 to 1:1.

步骤一，将垃圾焚烧飞灰与导电助热材料混合均匀，得到混合料，其中，导电助热材料选自炭黑、石墨、活性炭、焦粉或其组合，垃圾焚烧飞灰与导电助热材料的质量比为20:1～1:1。

[n0035]

Step 2, Preprocessing

步骤二，预处理

[n0036]

Before the mixture undergoes flash Joule heat treatment, it is placed in a flash Joule heating device and pretreated with low-pressure pulses to obtain the mixture.

将混合料进行闪蒸焦耳热处理前，将混合料放入闪焦耳加热设备中，通过低压脉冲预处理获得混合料。

[n0037]

The parameters for low-voltage pulse pretreatment are set as follows: discharge voltage 30-100V, single discharge time 0.1-1s, time interval 0.1-1s, and flash evaporation 1-3 times.

低压脉冲预处理的参数设置为：放电电压30～100V，单次放电时间0.1～1s，时间间隔为0.1～1s，闪蒸次数1～3次。

After low-pressure pulse pretreatment, the resistance of the mixture is measured. When the resistance of the mixture is ≤3Ω, flash joule heat treatment is performed.

低压脉冲预处理后对混合料进行电阻测定，当混合料的电阻≤3Ω后进行闪蒸焦耳热处理。

[n0038]

Step 3: The mixture is subjected to flash joule heat treatment, cooled, and the resulting waste incineration fly ash residue is obtained.

步骤三，将所述混合料进行闪蒸焦耳热处理，冷却并得到垃圾焚烧飞灰残渣。

The parameters for flash Joule heat treatment were set as follows: discharge voltage 80–380V, single discharge time 0.1–1s, time interval 0.5–2s, and flash treatment 1–5 times.

闪蒸焦耳热处理的参数设置为：放电电压80～380V，单次放电时间0.1～1s，时间间隔为0.5～2s，闪蒸次数1～5次。

[n0039]

To further illustrate the technical solution of the present invention, the following description is provided in conjunction with specific embodiment 1 and comparative examples 1 to 9.

为进一步说明本发明的技术方案，以下结合具体实施例1、对比例1～9进行阐述。

The raw materials, parameters, and steps used in the embodiments are all within the protection scope of this invention.

实施例所采用的原料、参数和步骤，均在本发明的保护范围内。

[n0040]

Example 1

实施例1

[n0041]

Fly ash emitted from the municipal solid waste incineration plant of Ordos Urban Mineral Research and Development Co., Ltd. was selected as raw material. The fly ash contains heavy metals such as Pb, Cd, and Zn. A pulsed electric flash reactor (model: FJH-2024APlus, Taiyuan Saiyin New Material Technology Co., Ltd.) was used to treat the fly ash from the waste incineration.

选取鄂尔多斯城市矿产研究开发有限责任公司生活垃圾焚烧厂排放的飞灰作为原料，该飞灰含有Pb、Cd、Zn等重金属，采用脉冲电闪蒸反应器(型号：FJH-2024APlus，太原赛因新材料科技有限公司)处理垃圾焚烧飞灰。

Figure 1(a) is a SEM+EDS image of the fly ash from waste incineration before treatment, showing the content of some heavy metal elements in the fly ash; Figure 2(a) is an XRD image of the fly ash from waste incineration before treatment; Figure 4(a) is a pore size distribution of the fly ash from waste incineration before treatment; Figure 5(a) is a Zn valence state distribution of the fly ash from waste incineration before treatment.

图1(a)为处理前垃圾焚烧飞灰的SEM+EDS图，可以看到飞灰中一些重金属元素的含量；图2(a)为处理前垃圾焚烧飞灰的XRD图；图4(a)为处理前垃圾焚烧飞灰的孔径分布；图5(a)为处理前垃圾焚烧飞灰的Zn金属价态分布图。

[n0042]

The collected fly ash was dried at 60°C for 12 hours and then ground through a 100-mesh sieve for later use.

将所采集的飞灰在60°C条件下烘干12小时，研磨过100目筛备用。

Weigh 2g of dry fly ash and mix it with carbon black at a mass ratio of 5:1 (i.e., fly ash: carbon black = 5:1) to obtain a uniform mixture. Then, put the mixture into a quartz tube and connect it to the Joule heat flash evaporation experimental platform.

称取2g干燥飞灰，与炭黑按质量比5:1混合(即飞灰：炭黑＝5:1)均匀得到混合料，随后将混合料放入石英管中，连接至焦耳热闪蒸实验平台。

First, a graphite electrode is inserted into one end of a quartz tube. Then, 1g of the mixture is added into the quartz tube, and another graphite electrode is inserted into the other end to compact the sample. The quartz tube is then placed on a flash Joule heating device, and the resistance of the sample is measured. By adjusting the knob of the flash Joule heating device, the degree of sample compression is adjusted, the compression ratio is changed, and the resistance is adjusted until the resistance is basically stable. Then, the sample is pretreated by discharging once at a low flash voltage of 60V and flashing once for 1s. After pretreatment, the resistance of the mixture drops to 3Ω, which meets the conditions for subsequent flash Joule treatment. Excessive resistance will cause a significant reduction in the current during the flash treatment process, significantly reducing heat generation and making it impossible to reach the high temperature required for evaporation or decomposition of heavy metals.

首先在石英管的一端插入一块石墨电极，然后在石英管中加入1g混合料，再从另一端插入另一块石墨电极并将样品压实，然后将石英管放在闪焦耳加热设备上，对样品的电阻进行检测，通过适当调整闪蒸焦耳热装置旋钮，调节样品的压缩程度，更改样品的压缩率，调节电阻，直至电阻基本稳定，之后将样品在60V的低闪蒸电压下放电1次，闪蒸1次，放电时间为1s进行预处理，预处理后混合料电阻降至3Ω，满足后续闪蒸焦耳处理条件，电阻过大会导致闪蒸处理过程电流显著减小，显著降低热量生成，无法达到蒸发或分解重金属所需的高温。

Subsequently, the sample was discharged once at a flash voltage of 150V, flashed once, and the single discharge time was 1s. The highest temperature generated by Joule heating was 2100°C. After cooling, the waste incineration fly ash residue was obtained and named FJH-150.

随后，将样品在闪蒸电压为150V下放电1次，闪蒸1次，单次放电时间为1s，焦耳热产生最高温度为2100°C，冷却，得到垃圾焚烧飞灰残渣，将所得到的垃圾焚烧飞灰残渣命名为FJH-150。

[n0043]

Figure 1(b) shows the SEM+EDS image of the treated waste incineration fly ash. Compared with Figure 1(a), it can be seen that the content of some heavy metal elements in the fly ash has been significantly reduced compared with that before treatment. Figure 2(b) shows the XRD pattern of the treated waste incineration fly ash. Compared with Figure 2(a), it can be seen that the peaks of the heavy metal compounds are reduced or even disappeared, indicating that the heavy metal compounds have been transformed. At the same time, the crystallinity of SiO2 is improved, which is conducive to the subsequent resource utilization of fly ash as building material raw material. Figure 3 shows the comparison of fly ash particle size distribution before and after treatment. After flash evaporation and Joule heating... After treatment, the fly ash particles melted, agglomerated, or restructured under high temperature, resulting in the merging of fine particles or an increase in the proportion of coarse particles. Figure 4(b) shows the pore size distribution of the treated waste incineration fly ash. Compared with Figure 4(a), it can be seen that after the volatiles such as heavy metal chlorides in the fly ash detached from the fly ash matrix, pores were left in situ, the micropore volume increased, and the fly ash structure was reshaped. Figure 5(b) shows the Zn metal valence state distribution of the treated waste incineration fly ash. Compared with Figure 5(a), it can be seen that the chemical structure of heavy metal Zn-containing compounds is less stable, making them more prone to decomposition or volatilization.

图1(b)为处理后垃圾焚烧飞灰的SEM+EDS图，对比图1(a)可以看到飞灰中一些重金属元素的含量相较于处理前有了明显的降低；图2(b)为处理后垃圾焚烧飞灰的XRD图，对比图2(a)可以到含有的重金属化合物峰减小，甚至消失，重金属化合物得到了转化，同时SiO₂结晶度提高，有利

于后续飞灰作为建材原料等资源化利用；图3为处理前后飞灰粒径分布对比图，经过闪蒸焦耳热处理后，飞灰颗粒在高温作用下发生了熔融、凝聚或结构重组，导致细颗粒合并或粗颗粒比例增加；图4(b)为处理后垃圾焚烧飞灰的孔径分布，对比图4(a)可以到飞灰重金属氯化物等挥发物脱离飞灰基质后，原位留下孔隙，微孔体积增加，飞灰结构得到重塑；图5(b)为处理后垃圾焚烧飞灰的Zn金属价态分布图，对比图5(a)可以到重金属含Zn化合物化学结构的稳定性降低，从而更易发生分解或挥发。

[n0044]

Comparative Example 1

对比例1

[n0045]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the flash evaporation voltage is 200V and the resulting waste incineration fly ash residue is named FJH-200.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，闪蒸电压为200V，所得垃圾焚烧飞灰残渣命名为FJH-200。

[n0046]

Comparative Example 2

对比例2

[n0047]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the flash evaporation voltage is 250V and the resulting waste incineration fly ash residue is named FJH-250.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，闪蒸电压为250V，所得垃圾焚烧飞灰残渣命名为FJH-250。

[n0048]

Comparative Example 3

对比例3

[n0049]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the flash evaporation voltage is 300V and the resulting waste incineration fly ash residue is named FJH-300.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，闪蒸电压为300V，所得垃圾焚烧飞灰残渣命名为FJH-300。

[n0050]

Comparative Example 4

对比例4

[n0051]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the fly ash:carbon black ratio is 3:1, and the resulting waste incineration fly ash residue is named FJH-1.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，飞灰：炭黑＝3:1，所得垃圾焚烧飞灰残渣命名为FJH-1。

[n0052]

Comparative Example 5

对比例5

[n0053]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the fly ash:graphite ratio is 5:1, and the resulting waste incineration fly ash residue is named FJH-2.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，飞灰：石墨＝5:1，所得垃圾焚烧飞灰残渣命名为FJH-2。

[n0054]

Comparative Example 6

对比例6

[n0055]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that 0.1g of the mixture is added to the quartz tube, and the resulting waste incineration fly ash residue is named FJH-3.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，在石英管中加入0.1 g混合料，所得垃圾焚烧飞灰残渣命名为FJH-3。

[n0056]

Comparative Example 7

对比例7

[n0057]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that 0.5g of the mixture is added to the quartz tube, and the resulting waste incineration fly ash residue is named FJH-4.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，在石英管中加入0.5 g混合料，所得垃圾焚烧飞灰残渣命名为FJH-4。

[n0058]

Comparative Example 8

对比例8

[n0059]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the sample is discharged once at a low flash voltage of 30V, and the resulting waste incineration fly ash residue is named FJH-5.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，将样品在30V的低闪蒸电压下放电1次，所得垃圾焚烧飞灰残渣命名为FJH-5。

[n0060]

Comparative Example 9

对比例9

[n0061]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the sample is discharged once at a low flash voltage of 80V, and the resulting waste incineration fly ash residue is named FJH-6.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，将样品在80V的低闪蒸电压下放电1次，所得垃圾焚烧飞灰残渣命名为FJH-6。

[n0062]

Comparative Example 10

对比例10

[n0063]

The method for removing heavy metals from waste incineration fly ash provided in this comparative example is the same as that in Example 1, except that the sample is discharged once at a flash voltage of 150V and flashed twice, with a single discharge time of 1s. The resulting waste incineration fly ash residue is named FJH-7.

本对比例提供的去除垃圾焚烧飞灰中重金属的方法与实施例1相同，区别仅在于，将样品在闪蒸电压为150V下放电1次，闪蒸2次，单次放电时间为1s，所得垃圾焚烧飞灰残渣命名为FJH-7。

[n0064]

Approximately 0.1000 g of the waste incineration fly ash residue obtained from Examples 1, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 were weighed and placed in a polytetrafluoroethylene digestion vessel. A mixed acid mixture of 6 mL of high-purity nitric acid (HNO3), 2 mL of high-purity hydrochloric acid (HCl), and 1 mL of hydrofluoric acid (HF) was added to promote the complete digestion of the waste incineration fly ash residue.

分别称取实施例1、对比例1、对比例2、对比例3、对比例4、对比例5、对比例6、对比例7、对比例8、对比例9、对比例10获得的垃圾焚烧飞灰残渣约0.1000g，置于聚四氟乙烯消解罐中，加入6mL高纯硝酸(HNO₃)、2mL高纯盐酸(HCl)和1mL氢氟酸(HF)的混合酸，以促进垃圾焚烧飞灰残渣完全消解。

After sealing the digestion vessel, place it in a microwave digester and set the program to heat to 180°C and hold for 20 minutes to complete the digestion.

消解罐密封后放入微波消解仪中，设定升温至180°C、保温20分钟的程序完成消解。

After digestion, allow the solution to cool naturally to room temperature. Transfer the digestion solution to a 50 mL volumetric flask and dilute to the mark with ultrapure water.

消解结束后自然冷却至室温，将消解液转移至50mL容量瓶中，用超纯水定容至刻度线。

At the same time, multiple sets of heavy metal standard solutions were prepared to establish a standard curve.

同时配制多组重金属标准溶液，用于建立标准曲线。

The determination was performed using an ICP-OES instrument. The determination wavelength and instrument parameters for the target element were set. After instrument calibration and background correction were completed, the sample solution, blank sample, parallel sample and spiked recovery sample were injected in sequence to ensure the accuracy and repeatability of the determination.

使用ICP-OES仪器进行测定，设定目标元素的测定波长和仪器参数，在完成仪器校准和背景校正后，依次进样测试样品溶液、空白样、平行样和加标回收样，以确保测定的准确性与重复性。

The content of each heavy metal element in fly ash is calculated based on the measured metal concentration, digestion liquid volume, and sample mass.

根据测得的金属浓度、消解液体积和样品质量计算飞灰中各重金属元素的含量。

[n0065]

The heavy metal content (mg/kg) is calculated using the following formula:

重金属含量(mg/kg)按下式计算：

[n0067]

Where: C_测 is the element concentration in the sample solution (mg/L); C_空 is the element concentration in the blank solution (mg/L); V is the total volume of the digestion solution (mL); and m is the sample mass (g).

其中：C_测为样品溶液中元素浓度(mg/L)；C_空为空白溶液中元素浓度(mg/L)；V为消解液总体积(mL)；m为样品质量(g)。

[n0068]

Table 1. Parameter data for Example 1 and Comparative Examples 1-10

表1实施例1，对比例1～10参数数据表

[n0070]

Table 2 Comparison of Heavy Metal Removal Rates (%) in Waste Incineration Fly Ash

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表2垃圾焚烧飞灰中重金属去除率(%)对比表

[n0073]

Example 1 (150V flash voltage, fly ash: carbon black = 5:1, 1g processing capacity) showed a moderate overall removal rate of heavy metals (Pb 60.53%, Cd 56.87%), but the difference was significant after adjusting the parameters.

实施例1(150V闪蒸电压、飞灰:炭黑＝5:1、1g处理量)对重金属的去除率整体适中(Pb 60.53%，Cd 56.87%)，而调整参数后差异显著。

Comparative Example 3 (300V voltage) showed a significant increase in heavy metal removal rate (Pb 90.46%), indicating that increasing the voltage can effectively enhance the Joule heating effect and promote the evaporation of heavy metals.

对比例3(300V电压)重金属去除率大幅提升(Pb 90.46%)，表明升高电压可有效强化焦耳热效应，促进重金属蒸发。

Comparative Example 6 (0.1g processing amount) achieved a Ni removal rate of 88.63%, indicating that reducing the sample amount is beneficial for efficient heat transfer, but in practical applications, the processing efficiency needs to be balanced.

对比例6(0.1g处理量)Ni去除率达88.63%，说明减少样品量利于高效热传递，但实际应用需平衡处理效率。

Comparative Example 4 (fly ash: carbon black = 3:1) and Comparative Example 5 (carbon black replaced by graphite) showed that although increasing the carbon black ratio (3:1) slightly improved the heavy metal removal rate, the effect of graphite decreased due to the difference in conductivity, confirming that carbon black is more suitable as a conductive material.

对比例4(飞灰:炭黑＝3:1)和对比例5(炭黑替换为石墨)对比显示，炭黑比例增加(3:1)虽小幅提升重金属去除率，但石墨因导电性差异导致效果下降，证实炭黑更适合作为导电材料。

It is worth noting that Comparative Example 8 (30V pretreatment) had an extremely low heavy metal removal rate (Cd was only 11.36%) because the resistance was not sufficiently reduced (resistance after pretreatment was greater than 3Ω), highlighting the importance of stabilizing the resistance during the pretreatment stage.

值得注意的是，对比例8(30V预处理)因电阻未充分降低(预处理后电阻大于3Ω)，重金属去除率极低(Cd仅11.36%)，凸显预处理阶段稳定电阻的重要性。

In summary, voltage, sample volume, and the ratio of conductive materials are important factors affecting heavy metal removal, while the resistance of the pretreatment mixture is a key factor affecting heavy metal removal. Optimization and coordination are needed to achieve efficient and economical treatment results.

综上，电压、样品量及导电材料配比是影响重金属去除的重要因素，预处理混合材料的电阻是影响重金属去除的关键因素，需优化协同以达到高效、经济的处理效果。

[n0074]

Based on the above-described preferred embodiments of the present invention, and through the above description, those skilled in the art can make various changes and modifications without departing from the technical concept of the present invention.

以上述依据本发明的理想实施例为启示，通过上述的说明内容，相关工作人员完全可以在不偏离本项发明技术思想的范围内，进行多样的变更以及修改。

The technical scope of this invention is not limited to the contents of the specification, but must be determined by the scope of the claims.

本项发明的技术性范围并不局限于说明书上的内容，必须要如权利要求范围来确定其技术性范围。