Notice

DESCRIPTION CN120557943A

Sleeve-type flash Joule heating device and heating method

套管式闪速焦耳加热装置及加热方法

[0001]

Technical Field

技术领域

[n0001]

This invention relates to the field of high-temperature material synthesis equipment technology, and in particular to a sleeve-type flash Joule heating device and heating method.

本发明涉及高温材料合成装备技术领域，尤其是涉及一种套管式闪速焦耳加热装置及加热方法。

[0003]

Background Technology

背景技术

[n0002]

Flash Joule Heating (FJH) technology has shown significant advantages in the preparation of advanced materials such as graphene, carbon nanotubes and silicon carbide due to its millisecond-level heating rate (>10^4 K/s) and ultra-high energy density (>1 kW・h/kg).

闪速焦耳加热(Flash Joule Heating,FJH)技术因其毫秒级升温速率(＞10^4K/s)和超高能量密度(＞1kW・h/kg)，在石墨烯、碳纳米管及碳化硅等先进材料的制备中展现出显著优势。

[n0003]

Traditional Joule heating devices mostly adopt a single-layer tube structure, which directly applies ohmic joule heating to the raw material through high-voltage pulses (>500V).

传统焦耳加热装置多采用单层管式结构，通过高压脉冲(＞500V)直接对原料施加欧姆焦耳加热。

However, such designs have inherent drawbacks: due to the uneven resistivity distribution of raw materials and the hysteresis effect of thermal diffusion, the radial temperature gradient can reach hundreds of degrees (taking 1500°C as an example), which leads to lattice distortion and performance degradation of the material.

然而，此类设计存在固有缺陷：由于原料电阻率分布不均及热扩散滞后效应，径向温度梯度可达上百度以上(以1500°C工况为例)，导致材料晶格畸变和性能劣化。

In response, related technologies have attempted to introduce an alumina ceramic isolation layer to homogenize heat flow and regulate the uniformity of the thermal field. However, at high temperatures (>1200°C), the ceramic material partially decomposes to form micron-sized residual particles (such as $Al_2O_3 \rightarrow Al + O_2\uparrow$), which contaminate the synthesis product and reduce its purity to below 95%.

对此，相关技术尝试引入氧化铝陶瓷隔离层以均化热流，调控热场的均匀性，但高温下(＞1200℃)陶瓷材料部分分解形成微米级残留颗粒(如Al2O3→Al+O2↑)，会污染合成产物并降低其纯度至95%以下。

[n0004]

Further research revealed that the traditional single-pulse excitation mode has an inherent limitation: during millisecond-level heating, the rate of Joule heat generation inside the raw material and the loss of external heat radiation are difficult to dynamically balance, resulting in a non-uniform temperature field distribution of "high in the center and low at the edge".

进一步研究发现，传统单脉冲激励模式存在本质局限：在毫秒级加热过程中，原料内部焦耳热生成速率与外部热辐射损失难以动态平衡，导致温度场呈现“中心高-边缘低”的非均匀分布。

[0007]

Summary of the Invention

发明内容

[n0005]

The present invention aims to solve at least one of the technical problems existing in the prior art.

本发明旨在至少解决现有技术中存在的技术问题之一。

Therefore, the purpose of this invention is to provide a sleeve-type flash Joule heating device and heating method, which aims to solve the problem of uneven temperature field distribution in existing Joule heating devices.

为此，本发明的目的在于提出一种套管式闪速焦耳加热装置及加热方法，旨在解决现有焦耳加热装置温度场分布不均匀的问题。

[n0006]

This invention proposes a sleeve-type flash Joule heating device, which includes a conductive sleeve, two first electrodes, two second electrodes, and a power supply system. The conductive sleeve is used to load the reaction raw materials, and the reaction raw materials contain conductive materials or conductive structures. The two first electrodes are electrically connected to both ends of the conductive sleeve along its axial direction. The two second electrodes are electrically connected to both sides of the conductive material or conductive structure along its axial direction. The power supply system is connected to the two first electrodes to form a first heating branch and to the two second electrodes to form a second

heating branch. The power supply system is adapted to provide direct current to the first and second heating branches. The power supply system includes a DC high-voltage pulse controller, which is adapted to control the on/off state of the first and second heating branches. A time-delay relay is provided on the second heating branch to control the conduction sequence of the second heating branch.

本发明提出了一种套管式闪速焦耳加热装置，套管式闪速焦耳加热装置包括导电套管、两个第一电极、两个第二电极和供电系统；导电套管用于装载反应原料，反应原料内设置有导电材料或导电结构；两个第一电极分别与导电套管的轴向两端电连接；两个第二电极分别与导电材料或导电结构的轴向两侧电连接；供电系统与两个第一电极连接，形成第一加热支路；且供电系统与两个第二电极连接，形成第二加热支路；供电系统适于向第一加热支路和第二加热支路提供直流电；其中，供电系统包括直流高压脉冲控制器，直流高压脉冲控制器适于控制第一加热支路和第二加热支路的通断；第二加热支路上设置有延时继电器，以适于控制第二加热支路的导通时序。

[n0007]

According to the sleeve-type flash Joule heating device of the present invention, two sets of electrodes are connected to the reaction raw materials (conductive materials or conductive structures) through conductive sleeves to construct two independent Joule heating circuits, one inside and one outside. The reaction raw materials are preheated by Joule heating through the outer conductive sleeve, and then the inner Joule heating is started. By utilizing

the dual thermal field coupling design, the temperature uniformity of the thermal field can be improved.

根据本发明的套管式闪速焦耳加热装置，通过导电套管与反应原料(导电材料或导电结构)分别连接两组电极，构建内外双个独立焦耳加热回路，通过外层导电套管焦耳预热反应原料，再启动内层焦耳加热，利用双热场耦合设计，能够提升热场的温度均匀性。

[n0008]

According to some embodiments of the present invention, the conductive bushing is made of hydrostatic graphite or tungsten.

根据本发明的一些实施例，导电套管采用静压石墨材料或钨材料制成。

[n0009]

According to some embodiments of the present invention, the wall thickness of the conductive sleeve is b, and b≥10mm; the diameter is d, and 100mm≤d≤200mm; the height is h, and 300mm≤h≤800mm.

根据本发明的一些实施例，导电套管的壁厚为b，且满足b≥10mm；直径为d，且满足100mm≤d≤200mm；高度为h，且满足300mm≤h≤800mm。

[n0010]

According to some embodiments of the present invention, the power supply system includes an input power supply and a rectifier circuit, the rectifier circuit including a transformer and a rectifier; the input power supply provides alternating current; the transformer is used to adjust the voltage of the alternating current; the rectifier is used to rectify the regulated alternating current into direct current.

根据本发明的一些实施例，供电系统包括输入电源和整流电路，整流电路包括变压器和整流器；输入电源提供交流电；变压器用于调整交流电的电压；整流器用于将调压后的交流电整流为直流电。

[n0011]

According to some embodiments of the present invention, the power supply system further includes a battery pack, which is connected in parallel with the rectifier circuit.

根据本发明的一些实施例，供电系统还包括蓄电池组，蓄电池组与整流电路并联设置。

[n0012]

According to some embodiments of the present invention, the reaction raw materials are filled in polyethylene bags, and the polyethylene bags are filled in conductive sleeves.

根据本发明的一些实施例，反应原料装填于聚乙烯袋中，聚乙烯袋装填于导电套管内。

[n0013]

According to some embodiments of the present invention, spiral grooves are formed on the surfaces of both the first electrode and the second electrode.

根据本发明的一些实施例，第一电极和第二电极的表面均形成有螺旋槽道。

[n0014]

According to some embodiments of the present invention, the pitch of the spiral channel is 0.5 mm and the depth is 0.1 mm.

根据本发明的一些实施例，螺旋槽道的螺距为0.5mm，深度为0.1mm。

[n0015]

This invention also proposes a flash Joule heating method, which utilizes the aforementioned sleeve-type flash Joule heating device. The flash Joule heating method includes the following steps:

本发明还提出了一种闪速焦耳加热方法，应用上述套管式闪速焦耳加热装置，闪速焦耳加热方法包括以下步骤：

[n0016]

The first heating branch is activated, and the reactants are preheated using a conductive sleeve for 0.1 to 1 second.

导通第一加热支路，先利用导电套管对反应原料进行预加热，预加热时间为0.1～1秒；

[n0017]

The second heating branch is activated to flash-heat the reaction raw materials for a period of 0.5 to 1 second.

导通第二加热支路，对反应原料进行闪速加热，闪速加热时间为0.5～1秒。

[n0018]

According to some embodiments of the present invention, while the reactants are being flash-heated, the reactants are also being heated using a conductive sleeve.

根据本发明的一些实施例，对反应原料进行闪速加热的同时，继续利用导电套管对反应原料进行加热。

[n0019]

Additional aspects and advantages of the invention will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention.

本发明的附加方面和优点将在下面的描述中部分给出，部分将从下面的描述中变得明显，或通过本发明的实践了解到。

[0023]

Attached Figure Description

附图说明

[n0020]

The above and/or additional aspects and advantages of the present invention will become apparent and readily understood from the description of the embodiments taken in conjunction with the following drawings, in which:

本发明的上述和/或附加的方面和优点从结合下面附图对实施例的描述中将变得明显和容易理解，其中：

[n0021]

Figure 1 is a schematic diagram of a sleeve-type flash Joule heating device according to some embodiments;

图1是根据一些实施例的套管式闪速焦耳加热装置的示意图；

[n0022]

Figure 2 is a schematic diagram of the temperature distribution when the sleeve-type flash Joule heating device of the present invention is heated compared with the prior art.

图2是本发明的套管式闪速焦耳加热装置与现有技术进行加热时的温度分布示意图；

[n0023]

Figure 3 is a comparison diagram of the radial temperature distribution when the sleeve-type flash Joule heating device of the present invention is heated with the prior art.

图3是本发明的套管式闪速焦耳加热装置与现有技术进行加热时的温度径向分布对比图；

[n0024]

Figure label:

附图标记：

[n0025]

1. Conductive sleeve; 2. Reaction material; 3. First electrode; 4. Second electrode; 5. DC high voltage pulse controller; 6. Time delay relay; 7. Transformer; 8. Rectifier; 9. Battery pack.

导电套管1；反应原料2；第一电极3；第二电极4；直流高压脉冲控制器5；延时继电器6；变压器7；整流器8；蓄电池组9。

[0030]

Detailed Implementation

具体实施方式

[n0026]

The embodiments of the present invention are described in detail below, examples of which are shown in the accompanying drawings, wherein the same or similar reference numerals denote the same or similar elements or elements having the same or similar functions throughout.

下面详细描述本发明的实施例，所述实施例的示例在附图中示出，其中自始至终相同或类似的标号表示相同或类似的元件或具有相同或类似功能的元件。

The embodiments described below with reference to the accompanying drawings are exemplary and are only used to explain the present invention, and should not be construed as limiting the present invention.

下面通过参考附图描述的实施例是示例性的，仅用于解释本发明，而不能理解为对本发明的限制。

[n0027]

The sleeve-type flash Joule heating device according to an embodiment of the present invention is described below with reference to FIG1.

下面参考图1描述根据本发明实施例的套管式闪速焦耳加热装置。

[n0028]

This invention proposes a sleeve-type flash Joule heating device, which includes a conductive sleeve 1, two first electrodes 3, two second electrodes 4, and a power supply system. The conductive sleeve 1 is used to load the reaction raw material 2, and the reaction raw material 2 is provided with a conductive material or conductive structure. The two first electrodes 3 are electrically connected to the two ends of the conductive sleeve 1 along their axial direction. The two second electrodes 4 are electrically connected to the two sides of the conductive material or conductive structure along their axial direction. The power supply system is connected to the two first electrodes 3 to form a first heating branch. The power supply system is also connected to the two second electrodes 4 to form a second heating branch. The power supply system is adapted to provide DC power to the first heating branch and the second heating branch. The power supply system includes a DC high-voltage pulse controller 5, which is adapted to control the on/off state of the first heating branch and the second heating branch. A time-delay relay 6 is provided on the second heating branch to control the conduction sequence of the second heating branch.

本发明提出了一种套管式闪速焦耳加热装置，套管式闪速焦耳加热装置包括导电套管1、两个第一电极3、两个第二电极4和供电系统；导电套管1用于装载反应原料2，反应原料2内设置有导电材料或导电结构；两个第一电极3分别与导电套管1的轴向两端电连接；两个第二电极4分别与导电材料或导电结构的轴向两侧电连接；供电系统与两个第一电极3连接，形成第一加热支路；且供电系统与两个第二电极4连接，形成第二加热支路；供电系统适于向第一加热支路和第二加热支路提供直流电；其中，供电系统包括直流高压脉冲控制器5，直流高压脉冲控制器5适于控制第一加热支路和第二加热支路的通断；第二加热支路上设置有延时继电器6，以适于控制第二加热支路的导通时序。

[n0029]

According to the sleeve-type flash Joule heating device of the present invention, the reaction raw material 2 is disposed inside the conductive sleeve 1, and the reaction raw material 2 is mixed with conductive material or conductive structure; the conductive sleeve 1 is connected to the power supply system through two first electrodes 3 to form a first heating branch. When the first heating branch is turned on, the conductive sleeve 1 heats up due to the current, which heats the reaction raw material 2 inside; the conductive material or conductive structure in the reaction raw material 2 is connected to the power supply system through two second electrodes 4 to form a second heating branch. When the second heating branch is turned on, the conductive material or conductive structure heats up and heats the reaction raw material 2.

根据本发明的套管式闪速焦耳加热装置，反应原料2设置于导电套管1内部，反应原料2中混合有导电材料或导电结构；导电套管1通过两个第一电极3与供电系统连接，形成第一加热支路，第一加热支路导通时，导电套管1由于电流作用发热，对内部的反应原料2起到加热作用；反应原料2中的导电材料或导电结构通过两个第二电极4与供电系统连接，形成第二加热支路，第二加热支路导通时，导电材料或导电结构发热而对反应原料2起到加热作用。

The DC high-voltage pulse controller 5 controls the on/off state of the first heating branch and the second heating branch, injects pulse energy into the first heating branch and the second heating branch, and controls the timing and duration of the pulse voltage signal. The time delay relay 6 controls the pulse sequence of the two heating branches, and can control the second heating branch to conduct with a delay relative to the first heating branch.

直流高压脉冲控制器5控制第一加热支路和第二加热支路的通断，对第一加热支路和第二加热支路实现脉冲能量注入，控制脉冲电压信号的发生时刻和时长；延时继电器6控制两个加热支路的脉冲先后时序，可以控制第二加热支路相对第一加热支路延时导通。

When the first heating branch is turned on, the conductive sleeve 1 preheats the reaction material 2 under the action of current. After the second heating branch is turned on with a delay, the conductive material or conductive structure flash-heats the reaction material 2 under the action of current.

第一加热支路先导通时，导电套管1在电流作用下对反应原料2进行预加热，第二加热支路延迟导通后，导电材料或导电结构在电流作用下对反应原料2进行闪速加热。

[n0030]

According to the sleeve-type flash Joule heating device of the present invention, two sets of electrodes are connected to the reaction raw material 2 (conductive material or conductive structure) through the conductive sleeve 1, respectively, to construct two independent Joule heating circuits inside and outside. The reaction raw material 2 is preheated by the outer conductive sleeve 1, and then the inner Joule heating is started. By utilizing the dual thermal field coupling design, the temperature uniformity of the thermal field can be improved.

根据本发明的套管式闪速焦耳加热装置，通过导电套管1与反应原料2(导电材料或导电结构)分别连接两组电极，构建内外双个独立焦耳加热回路，通过外层导电套管1焦耳预热反应原料2，再启动内层焦耳加热，利用双热场耦合设计，能够提升热场的温度均匀性。

[n0031]

In some embodiments, the resistivity of the conductive sleeve 1 is ρ₁, and satisfies ρ₁＜5×10⁻⁶Ω・m, exhibiting low resistance

characteristics; the resistivity of the conductive material or conductive structure in the reaction raw material 2 is ρ₂, and satisfies ρ₂＞1×10⁻³Ω・m, exhibiting high resistance characteristics.

在一些实施例中，导电套管1的电阻率为ρ₁，且满足ρ₁＜5×10⁻⁶Ω・m，具有低电阻特性；反应原料2中的导电材料或导电结构的电阻率为ρ₂，且满足ρ₂＞1×10⁻³Ω・m，具有高电阻特性。

The first heating branch is turned on first, and the low resistance of the conductive sleeve 1 can generate a large current (>2000A) for preheating. The second heating branch is turned on with a delay. Through the high resistance of the anti-conductive material or conductive structure, local energy focusing can be achieved, and finally a temperature compensation effect is formed in the central region of the reaction raw materials, suppressing heat loss at the edge.

第一加热支路优先导通，利用导电套管1的低电阻特性可以形成大电流(＞2000A)预加热；延迟导通第二加热支路，通过反导电材料或导电结构的高电阻特性，能够实现局部能量聚焦，最终在反应原料中心区域形成温度补偿效应，抑制热边缘损失。

[n0032]

In the above embodiment, the conductive sleeve 1 is used to preheat the reaction material 2 in the initial pulse stage, so that the reaction material 2 is preheated to 500°C to 800°C. After a delay of 0.1 to 1 second, the reaction material 2 completes flash heating in the second pulse stage. The flash heating time is 0.5 to 1 second, so that the reaction material 2 is preheated to above 1500°C.

上述实施例中，利用导电套管1在初始脉冲阶段对反应原料2进行预加热，使反应原料2预升温至500°C～800°C，0.1～1秒延迟后，反应原料2在第二脉冲阶段完成闪速加热，闪速加热时间为0.5～1秒，使反应原料2预升温至1500°C以上。

After testing, as shown in Figures 2 and 3, Figure 2(a) is a schematic diagram of the temperature distribution of the device during heating in the prior art; Figure 2(b) is a schematic diagram of the temperature distribution of the sleeve-type flash Joule heating device of the present invention during heating; Figure 3 is a comparison diagram of the radial temperature distribution of the sleeve-type flash Joule heating device of the present invention and the prior art during heating. This gradient heating mode can improve the radial uniformity of the temperature field of the reaction raw material 2 to within ±10%, while the temperature field uniformity of the traditional conductive sleeve 1 Joule heating structure is above ±30%. Compared with the prior art, this embodiment can significantly improve the uniformity of the temperature field.

经过测试，如图2、图3所示，图2(a)是现有技术进行加热时装置的温度分布示意图；图2(b)是本发明的套管式闪速焦耳加热装置加热时的温度分布示意图；图3是本发明的套管式闪速焦耳加热装置与现有技术进行加热时的温度径向分布对比图；该梯度加热模式可以使反应原料2的温度场径向均匀性提升至±10%以内，而传统导电套管1焦耳加热结构的温度场均匀性在±30%以上，相较于现有技术，本实施例可以显著提升温度场的均匀性。

[n0033]

Furthermore, in use, the sleeve-type flash Joule heating device of the present invention dynamically adjusts the pulse width and voltage amplitude of the two sets of electrodes according to the real-time load impedance, distributes pulse energy, ensures that the total energy density is greater than 1.5 kW・h/kg, and avoids electrode overload and ablation.

进一步地，本发明的套管式闪速焦耳加热装置在使用时，直流高压脉冲控制器5根据实时负载阻抗动态调整两组电极的脉冲宽度和电压幅值，分配脉冲能量，确保总能量密度大于1.5kW・h/kg，同时避免电极过载烧蚀。

In some embodiments, the DC high-voltage pulse controller 5 controls the pulse width to be 0.5 to 1 second, controls the voltage amplitude of the first heating branch to be 540V to 800V, and controls the voltage amplitude of the second heating branch to be 800V to 1350V, so as to meet the thermal reaction requirements.

在一些实施例中，直流高压脉冲控制器5控制脉冲宽度为0.5～1秒，控制第一加热支路的电压幅值为540V～800V，控制第二加热支路的电压幅值为800V～1350V，以满足热反应需求。

[n0034]

According to some embodiments of the present invention, the conductive sleeve 1 is made of hydrostatic graphite or tungsten.

根据本发明的一些实施例，导电套管1采用静压石墨材料或钨材料制成。

In this embodiment, the conductive sleeve 1, made of hydrostatic graphite or tungsten material, has high conductivity and high temperature resistance.

在本实施例中，采用静压石墨材料或钨材料制成的导电套管1具有高导电性和耐高温性能。

[n0035]

According to some embodiments of the present invention, the wall thickness of the conductive sleeve 1 is b, and b≥10mm; the diameter is d, and 100mm≤d≤200mm; the height is h, and 300mm≤h≤800mm.

根据本发明的一些实施例，导电套管1的壁厚为b，且满足b≥10mm；直径为d，且满足100mm≤d≤200mm；高度为h，且满足300mm≤h≤800mm。

In this embodiment, the structural dimensions of the conductive sleeve 1 are set as described above, which can achieve a smaller resistance while ensuring structural strength, so as to have good conductivity.

在本实施例中，导电套管1的结构尺寸如上述设置，可以在保证结构强度的基础上，实现较小的电阻，以具有良好的导电性能。

[n0036]

According to some embodiments of the present invention, the power supply system includes an input power supply and a rectifier circuit, the rectifier circuit including a transformer 7 and a rectifier 8; the input power supply provides alternating current; the transformer 7 is used to adjust the voltage of the alternating current; the rectifier 8 is used to rectify the regulated alternating current into direct current.

根据本发明的一些实施例，供电系统包括输入电源和整流电路，整流电路包括变压器7和整流器8；输入电源提供交流电；变压器7用于调整交流电的电压；整流器8用于将调压后的交流电整流为直流电。

In this embodiment, the input power supply is connected to the rectifier circuit, which is connected to the first heating branch and the second heating branch. The rectifier circuit can adjust the heating voltage and convert AC power to DC power.

在本实施例中，输入电源与整流电路连接，整流电路连接第一加热支路和第二加热支路，整流电路可以调整加热电压，并将交流电改为直流电。

In some embodiments, the input power supply can be 380V industrial power, which is convenient to obtain; the transformer 7 is a three-phase transformer 7, with the secondary winding connected in a star configuration, and the transformer 7 can boost the voltage to 400V~1000V; the rectifier 8 is a full-wave rectifier 8 composed of six diodes, which can rectify the boosted AC power into DC power, and the voltage range of the rectified DC power is 540V~1350V.

在一些实施例中，输入电源可选用380V的工业用电，取电方便；变压器7选用三相变压器7，次级绕组以星形连接，变压器7可以将电压升高至400V～1000V；整流器8选用六个二极管组成的全波整流器8，可以将升压后的交流电整流为直流电，整流后的直流电的电压范围为540V～1350V。

[n0037]

It should be noted that if the input power is drawn from the grid, fluctuations in the grid input voltage (above ±15%) will be directly coupled to the heating circuit, causing local

temperature drift (>±10%), which will seriously affect the batch consistency of the synthesized products.

需要注意的是，输入电源若在电网取电，电网输入电压波动(±15%以上)会直接耦合至加热回路，引发局部温度漂移(＞±10%)，严重影响合成产物的批次一致性。

[n0038]

To address the aforementioned problems, according to some embodiments of the present invention, the power supply system further includes a battery pack 9, which is connected in parallel with the rectifier circuit.

针对上述问题，根据本发明的一些实施例，供电系统还包括蓄电池组9，蓄电池组9与整流电路并联设置。

In this embodiment, the rectifier circuit and the battery pack 9 are connected in parallel to form a hybrid power supply topology circuit.

在本实施例中，整流电路与蓄电池组9并联，组成混合供电拓扑电路。

When the grid voltage fluctuates or the rectifier circuit malfunctions, the battery pack 9 responds quickly to compensate for voltage drops and uses its equivalent internal resistance

to suppress grid voltage fluctuations and current fluctuations, thereby improving current stability to ±2%. At the same time, it can also compensate for the transient power shortage of the transformer 7 through its fast response characteristics.

当电网电压波动或整流电路异常时，蓄电池组9快速响应，可以补偿电压跌落，并利用等效内阻抑制电网波动电压，抑制电流波动，可以提升电流稳定度至±2%；同时还可以通过快速响应特性补偿变压器7暂态功率缺口。

The fast response characteristic of battery pack 9 means that battery pack 9 can output a 500A pulse current within 5 seconds.

蓄电池组9的快速响应特性是指蓄电池组9可在5秒内输出500A脉冲电流。

[n0039]

Specifically, the positive terminal of the DC output of the three-phase full-wave rectifier circuit is electrically connected to the positive bus of the battery pack 9, and the negative terminal of the DC output of the three-phase full-wave rectifier circuit is electrically connected to the negative bus of the battery pack 9, forming a stable parallel power supply architecture.

具体地，三相全波整流电路直流输出端的正极与蓄电池组9的正极母线电性连接，三相全波整流电路直流输出端的负极与蓄电池组9的负极母线电性连接，形成稳定的并联供电架构。

When the three-phase full-wave rectifier circuit is in operation, its DC output charges the battery pack 9 through the parallel power supply architecture; when the three-phase full-wave rectifier circuit is not in operation or the output is abnormal, the battery pack 9 discharges to the DC bus through the parallel power supply architecture, and supplies power to the first heating branch and the second heating branch in combination with the DC output of the three-phase full-wave rectifier circuit.

当三相全波整流电路处于工作状态时，其直流输出通过所述并联供电架构向蓄电池组9充电；当三相全波整流电路处于非工作状态或输出异常时，蓄电池组9通过所述并联供电架构向直流母线放电，结合三相全波整流电路的输出直流电向第一加热支路和第二加热支路供电。

The battery pack 9, through its energy storage characteristics and in conjunction with the parallel power supply architecture, suppresses DC bus current fluctuations and effectively prevents inrush currents, maintaining the stability of the Joule heating current, thus ensuring the consistency and repeatability of the thermal reaction process.

蓄电池组9通过其电能存储特性与所述并联供电架构共同作用，抑制直流母线电流波动并有效防止出现冲击电流，维持焦耳加热电流的稳定性，使得热反应过程具有一致性和可重复性。

[n0040]

Among them, the equivalent internal resistance of battery pack 9 is less than 0.189Ω, ensuring high-efficiency output and reducing energy loss; the battery capacity is designed to be at least 5Ah to ensure stable system operation and the ability to perform multiple high-intensity discharges; the output voltage of battery pack 9 is adapted to the voltage range after rectification by the rectifier circuit, specifically 540V～1350V; battery pack 9 can pass a maximum current of 500A within 5 seconds in a single working cycle and support at least 5 such working cycles.

其中，蓄电池组9的等效内阻小于0.189Ω，确保高效能输出并减少能量损失；电池容量设计至少达到5Ah，以保障系统的稳定运行与多次高强度放电的能力；蓄电池组9的输出电压适应整流电路整流后的电压范围，具体为540V～1350V；蓄电池组9能够在单一工作循环中，于5秒内通过最高达500A的电流，并支持至少5次这样的工作循环。

[n0041]

According to some embodiments of the present invention, the reaction raw material 2 is filled in a polyethylene bag, and the polyethylene bag is filled in the conductive sleeve 1.

根据本发明的一些实施例，反应原料2装填于聚乙烯袋中，聚乙烯袋装填于导电套管1内。

In this embodiment, a polyethylene bag is used to hold the reaction material 2. The polyethylene bag is placed between the conductive sleeve 1 and the reaction material 2, which can serve as a spacer and facilitate the process of filling the reaction material 2 into the conductive sleeve 1.

在本实施例中，利用聚乙烯袋盛装反应原料2，聚乙烯袋处于导电套管1与反应原料2之间，可以起到间隔作用，同时可以便利反应原料2装填至导电套管1中的操作过程。

Furthermore, during the flash heating process, the polyethylene bag generates short-chain hydrocarbon gas (C_xHγ) through pyrolysis. This gas can serve as a reducing atmosphere to protect the reaction raw material 2, and can also eliminate the contact thermal resistance between the conductive sleeve 1 and the reaction raw material 2 through the vaporization expansion effect.

进一步地，在闪速加热过程中，聚乙烯袋通过热解生成短链碳氢气体(C_xHγ)，既可以作为还原气氛保护反应原料2，又可以通过气化膨胀效应消除导电套管1与反应原料2间的接触热阻。

Furthermore, during the flash heating process, the polyethylene bag will eventually undergo complete pyrolysis and transformation, decomposing into CO₂ and H₂O without leaving any residue. Therefore, it will not contaminate the synthesized product or affect its purity.

更进一步地，在闪速加热的过程中，聚乙烯袋最终会完全热解转化，分解为CO₂和H₂O，不留残余物，故而不会污染合成产物，不会影响合成产物的纯度。

In some embodiments, the thickness of the polyethylene bag may be configured to be 0.025 mm to 0.3 mm.

在一些实施例中，聚乙烯袋的厚度可构造为0.025mm～0.3mm。

[n0042]

It should also be noted that in Joule heating technology, existing electrode structures are prone to arcing under ultra-high current (>1000A) due to uneven current density distribution on the contact surface (standard deviation >15%), which can easily cause electrode erosion and shorten lifespan.

还需要注意的是，在焦耳加热的相关技术中，现有电极结构因接触面电流密度分布不均(标准差＞15%)，在超高电流(＞1000A)下易引发电弧放电，易造成电极烧蚀和寿命缩短。

[n0043]

To address the above-mentioned problems, according to some embodiments of the present invention, spiral grooves are formed on the surfaces of both the first electrode 3 and the second electrode 4.

针对上述问题，根据本发明的一些实施例，第一电极3和第二电极4的表面均形成有螺旋槽道。

In this embodiment, by setting a spiral channel, the local current path can be changed, the edge effect can be dispersed, the current can be distributed more evenly, and the anti-arc performance can be improved.

在本实施例中，通过设置螺旋槽道可以改变局部电流路径，分散边缘效应，使得电流更均匀地分布，提升抗电弧性能。

[n0044]

According to some embodiments of the present invention, the pitch of the spiral channel is 0.5 mm and the depth is 0.1 mm.

根据本发明的一些实施例，螺旋槽道的螺距为0.5mm，深度为0.1mm。

In this embodiment, the spiral channel is constructed with the above-mentioned dimensions, which can effectively optimize the current distribution and reduce the contact resistance.

在本实施例中，螺旋槽道构造为上述尺寸，可以有效优化电流分布，降低接触电阻。

Tests show that, compared to planar electrodes, this embodiment can reduce the standard deviation of current density distribution from 15% to less than 5% of that of traditional planar electrodes. Combined with timing pulse control, the lifespan of the electrode in this embodiment can be increased to more than 1,000 cycles, compared to the lifespan of less than 200 cycles of traditional electrodes. At the same time, the electrode in this embodiment can reduce the contact resistance to below 50 μΩ.

测试得到，相较于平面电极，本实施例可以将电流密度分布标准差从传统平面的15%降低至5%以内，结合时序脉冲控制，相较于传统电极低于200次的使用寿命，本实施例的电极寿命可以提升至1000次以上；同时，本实施例的电极可以降低接触电阻至50μΩ以下。

[n0045]

According to some embodiments of this application, the first electrode 3 and the second electrode 4 can be made of copper-tungsten alloy or graphite, which have good electrical conductivity, thermal conductivity and high temperature resistance.

根据本申请的一些实施例，第一电极3和第二电极4可采用铜钨合金或石墨制成，具有良好的导电性、导热性以及耐高温性能。

[n0046]

In combination with the above embodiments, the present invention solves the problems of uneven temperature and power grid fluctuation in traditional flash Joule heating devices through multiple technical innovations such as internal and external dual thermal field coupling design, timed pulse energy injection, hybrid power supply topology circuit, and anti-arc electrode optimization, and significantly improves the quality of products synthesized using the sleeve-type flash Joule heating device of the present invention.

结合上述各实施例，本发明通过内外双热场耦合设计、时序化脉冲能量注入、混合供电拓扑电路以及抗电弧电极优化等多项技术创新，解决了传统闪速焦耳加热装置存在的温度不均和电网波动问题，显著提升了利用本发明套管式闪速焦耳加热装置合成产物的质量。

[n0047]

This invention also proposes a flash Joule heating method, which utilizes the aforementioned sleeve-type flash Joule heating device. The flash Joule heating method includes the following steps:

本发明还提出了一种闪速焦耳加热方法，应用上述套管式闪速焦耳加热装置，闪速焦耳加热方法包括以下步骤：

[n0048]

The first heating branch is turned on, and the reaction raw material 2 is preheated using the conductive sleeve 1 for 0.1 to 1 second;

导通第一加热支路，先利用导电套管1对反应原料2进行预加热，预加热时间为0.1～1秒；

[n0049]

The second heating branch is activated to flash-heat the reaction material 2 for 0.5 to 1 second.

导通第二加热支路，对反应原料2进行闪速加热，闪速加热时间为0.5～1秒。

[n0050]

According to the flash Joule heating method of the present invention, the first heating branch containing the conductive sleeve 1 is first turned on, so that the conductive sleeve 1 preheats the reactant 2. The low resistance of the conductive sleeve 1 generates a large current, and the reactant 2 can be preheated to 500-800°C within 0.1 to 1 second, which can realize the

initial temperature rise of the reactant 2 from the outside to the inside and establish an initial temperature gradient. Then, the second heating branch containing the reactant 2 is turned on, and the high resistance of the conductive material or conductive structure in the reactant 2 is used to realize local energy focusing, which flash heats the central region of the reactant 2. The central region is heated to above 1500°C within 0.5 to 1 second, which can realize the further temperature rise of the reactant 2 from the inside to the outside and can homogenize the radial temperature field.

根据本发明的闪速焦耳加热方法，先导通导电套管1所在的第一加热支路，使导电套管1对反应原料2进行预加热，利用导电套管1的低电阻特性形成大电流，0.1～1秒内可以将反应原料预热至500～800°C，能够实现反应原料2由外向内导热的初步升温，建立初始的温度梯度；再导通反应原料2所在的第二加热支路，利用反应原料2内的导电材料或导电结构的高电阻特性实现局部能量聚焦，对反应原料2中心区域进行闪速加热，0.5～1秒内使中心区域加热至1500°C以上，可以实现反应原料2由内向外导热的进一步升温，能够均匀化径向温度场。

This method reduces the temperature gradient and significantly improves the uniformity of the temperature field by using staged heating and combining internal and external heat sources.

本方法通过分阶段加热和内外热源结合的方式，减少温度梯度，能够显著提高温度场的均匀性。

[n0051]

As shown in Figures 2 and 3, it is clear that compared with the prior art, the present invention can significantly improve the uniformity of temperature distribution.

如图2、图3所示，可以明显看出，相比现有技术，本发明能够显著提升温度分布的均匀性。

[n0052]

According to some embodiments of the present invention, while the reactant 2 is being flash-heated, the reactant 2 is also being heated using the conductive sleeve 1.

根据本发明的一些实施例，对反应原料2进行闪速加热的同时，继续利用导电套管1对反应原料2进行加热。

In this embodiment, during flash heating, the conductive sleeve 1 and the internal conductive material or conductive structure are heated simultaneously. The conductive sleeve 1 can maintain the temperature of the reaction material 2 in the edge area, compensate for the heat exchange loss between the reaction material 2 and the external environment through the conductive sleeve 1, suppress heat edge loss, thereby reducing the temperature gradient and

improving the uniformity of temperature distribution. The conductive sleeve 1 and the internal conductive material work together to achieve more precise temperature distribution control.

在本实施例中，闪速加热时，对导电套管1和内部导电材料或导电结构同时导电进行加热，导电套管1能够维持边缘区域反应原料2的温度，补偿反应原料2透过导电套管1与外部环境的热交换损失，抑制热边缘损失，从而减少温度梯度，提升温度分布的均匀性；导电套管1和内部导电材料形成协同作用，实现更精确的温度分布控制。

[n0053]

Furthermore, at the end of flash heating, the heating branch of the reactant 2 can be disconnected first, and then the heating branch of the conductive sleeve 1 can be disconnected. The uniformity of temperature distribution can be further improved by using the heating of the conductive sleeve 1.

进一步地，在闪速加热结束时，可以先断开反应原料2的加热支路，再断开导电套管1的加热支路，利用导电套管1加热进一步提升温度分布的均匀性。

[n0054]

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。

[n0055]

In the description of this invention, "first feature" and "second feature" may include one or more of the features.

在本发明的描述中，“第一特征”“第二特征”可以包括一个或者更多个该特征。

[n0056]

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

在本发明的描述中，“多个”的含义是两个或两个以上。

[n0057]

In the description of this invention, the first feature being "above" or "below" the second feature may include the first and second features being in direct contact, or it may include the first and second features not being in direct contact but being in contact through another feature between them.

在本发明的描述中，第一特征在第二特征“之上”或“之下”可以包括第一和第二特征直接接触，也可以包括第一和第二特征不是直接接触而是通过它们之间的另外的特征接触。

[n0058]

In the description of this invention, the terms "above," "over," and "on top" for the first feature and the second feature include the first feature being directly above or diagonally above the second feature, or simply indicate that the first feature is at a higher horizontal level than the second feature.

在本发明的描述中，第一特征在第二特征“之上”“上方”和“上面”包括第一特征在第二特征正上方和斜上方，或仅仅表示第一特征水平高度高于第二特征。

[n0059]

In the description of this specification, references to terms such as "an embodiment," "some embodiments," "illustrative embodiment," "example," "specific example," or "some examples," etc., refer to specific features, structures, materials, or characteristics described in connection with that embodiment or example that are included in at least one embodiment or example of the present invention.

在本说明书的描述中，参考术语“一个实施例”“一些实施例”“示意性实施例”“示例”“具体示例”或“一些示例”等的描述意指结合该实施例或示例描述的具体特征、结构、材料或者特点包含于本发明的至少一个实施例或示例中。

In this specification, the illustrative expressions of the terms used above do not necessarily refer to the same embodiments or examples.

在本说明书中，对上述术语的示意性表述不一定指的是相同的实施例或示例。

Furthermore, the specific features, structures, materials, or characteristics described may be combined in any suitable manner in one or more embodiments or examples.

而且，描述的具体特征、结构、材料或者特点可以在任何的一个或多个实施例或示例中以合适的方式结合。

[n0060]

Although embodiments of the invention have been shown and described, those skilled in the art will understand that various changes, modifications, substitutions and alterations can be made to these embodiments without departing from the principles and spirit of the invention, the scope of which is defined by the claims and their equivalents.

尽管已经示出和描述了本发明的实施例，本领域的普通技术人员可以理解：在不脱离本发明的原理和宗旨的情况下可以对这些实施例进行多种变化、修改、替换和变型，本发明的范围由权利要求及其等同物限定。