ISSN 2616-5767 Vol.8, Issue 2: 90-95, DOI: 10.25236/AJETS.2025.080212

Research progress of acoustic resonance hybrid technology and its application

Jiang Kefei[1], Zhu Zihan[1,a,*], Liu Kesheng[1]

[1]*Nanjing University of Science and Technology, Nanjing, China*
[a]*940821262@qq.com*
**Corresponding author*

Abstract: *Resonant Acoustic Mixing (RAM) technology, an emerging blade-free full-field mixing method developed by ResoDyn Corporation in Montana, USA, offers significant advantages over conventional mixing techniques by eliminating blade-induced material shear and substantially reducing mechanical stimulation. This innovative approach demonstrates exceptional potential for energetic material processing due to its unique combination of rapid mixing efficiency, superior homogenization performance, and minimized waste generation. Extensive international research has not only validated the technical feasibility of RAM but also facilitated its industrial implementation in specialized production scenarios. The following sections systematically present domestic and international advancements in RAM technology through comprehensive analysis of its operational principles, equipment configurations, and practical applications.*

Keywords: *Resonant Acoustic Mixing; Equipment; Application*

1. Introduction

Resonant Acoustic Mixing (RAM), an innovative full-field blending technology emerging in recent years, was developed by ResoDyn Corporation (Montana, USA) under funding from the Missile Defense Agency of Naval Air Warfare Center Weapons Division at China Lake, Pennsylvania. This methodology exploits the resonance characteristics of spring-mass systems to induce low-frequency (≈60 Hz), high-acceleration (0-1200 m/s^2) vibrations in mixing vessels with minimal energy input. The resultant synergistic coupling between macroscopic vibrational blending and microscopic acoustic streaming enables boundary condition disruption for homogeneous material dispersion across the entire processing domain [1-2]. Distinct from conventional techniques, RAM eliminates mechanical agitators (impellers/screws) to avoid shear-induced material degradation, circumvents rotational speed limitations inherent in centrifugal methods for enhanced productivity, prevents localized cavitation effects characteristic of ultrasonic processing to facilitate industrial-scale implementation, and surpasses gravitational mixing efficiency particularly in high-viscosity systems [3-5]. Its military applications have expanded significantly, encompassing propellant formulation, PBX/eutectic explosive synthesis, and nano-thermite production. Recognized by UK Defense Ministry armaments specialist Philip Cheese as "a disruptive technology with potential to redefine ammunition manufacturing paradigms" [6-7], RAM continues to demonstrate transformative capabilities. This review systematically examines current research advancements in RAM fundamentals, equipment configurations, and practical implementations.

2. Acoustic Resonance Mixing Principle

Acoustic resonance technology is based on the resonance of the driving system and the spring system, which realizes the low-frequency and high-acceleration vertical vibration of the container under the condition of small input energy, and produces the coupling effect of macro-vibration dispersion and micro-acoustic flow dispersion in the mixed material, thus producing multiphase flow to achieve the mixing effect.

Acoustic resonance instrument can realize both macro dispersion of vibration and micro dispersion of sound waves at the maximum acceleration of 100 g (1g = 9.8m/s), and is widely used in solid-solid, solid-liquid, liquid-liquid, gas-liquid and other material systems [4]. Especially the nano-material system and high viscosity material system which are easy to agglomerate; The dispersion efficiency is up to 2-10 times higher than that of traditional dispersion methods such as stirring. For the conventional mixed material system, the dispersion time generally does not exceed 10min, and the dispersion time does not extend with the increase of the order of the mixed material.

3. Acoustic Resonance Mixing Principle

Taking the acoustic resonance mixing system developed by Xi 'an Institute of Modern Chemistry as an example, the system includes vibration exciter, frequency modulator, power amplifier, blower, mixing cylinder and other components, which can realize the functions of frequency adjustment, amplitude adjustment and instrument air cooling in the mixing process [8].

The most important part is the special vibration exciter of the resonant machinery which can generate the acoustic energy field. The resonance of the mechanical system will introduce the low-frequency resonant acoustic energy into the mixing matrix (solid-solid, solid-liquid, liquid-liquid and liquid-gas mixture), and the propagation of acoustic waves in the whole mixing matrix will form a large mixing area, which is also called body acoustic flow. In this way, micro-scale eddy current (micro-acoustic flow) and local mixing (bulk acoustic flow) are formed in the whole mixed medium [9-11]. The realization of this acoustic resonance mixing requires proprietary and unique control technology, and the mechanical energy of the system is efficiently transferred to the material of the mixing container through the sound pressure wave propagation in the payload.

At present, the acoustic resonance mixing equipment abroad is basically dominated by ResoDyn. ResoDyn's products include LabRAM I (load capacity 500g) and LabRAM II (load capacity 1000g) for laboratory R&D, OmniRAM (load capacity 5kg) for large-scale R&D and small-scale production and processing, RAM 5 (load capacity 36kg) and RAM 55 (load capacity 420kg) for medium-scale production and processing, all of which have Pharma suitable for drug mixing. If the customer needs continuous mixing, ResoDyn can also customize the continuous operation acoustic resonance mixing system (CAM System) with OmniRAM, RAM 5 or RAM 55 for customers, which can realize Qualcomm continuous acoustic resonance mixing of various materials [3].

At present, China has mastered the principle and design method of acoustic resonance hybrid equipment. Huazhong University of Science and Technology, Xi 'an Jiaotong University, Xi 'an Institute of Modern Chemistry, Institute of Aerospace Chemical Technology and other units have developed some RAM equipment, with the largest scale reaching 100kg [2,4,12-14]. Shenzhen Acoustic Resonance Technology Co., Ltd. and Shenzhen Huasheng Strengthening Technology Co., Ltd. have realized the commercial production of acoustic resonance mixing equipment. Among them, the products of Shenzhen Acoustic Resonance Technology Co., Ltd. includeRAMixers G500 model(load capacity 500g),RAMixers G2000 model(load capacity 2kg),RAMixers GF2000 explosion-proof type(load capacity 2kg),RAMixers G5000 model(load capacity 5kg) and RAMixers GL30 pilot model(Load capacity 30kg) [15-16]. The products of Shenzhen Huasheng Strengthening Technology Co., Ltd. include HAM100 (load capacity 100g), HAM500 (load capacity 500g), HAM2000 (load capacity 2kg), HAM5L (load capacity 5kg), HAM50L and HAM200L(HAM50L and HAM200L are customized production) [17].It can be seen that China has made great progress in acoustic resonance mixing equipment at present, and the technical level is close to ResoDyn company.

4. Acoustic Resonance Mixed Application

4.1. Application of Acoustic Resonance Mixing Technology in Preparation of Energetic Materials

4.1.1. Participate in the Preparation of Eutectic Explosives

Eutectic explosive is a kind of crystal which mixes different explosives at molecular level through intermolecular force. By forming eutectic explosives, the oxygen balance and sensitivity of some explosives can be effectively improved, and their explosion heat, work ability and safety can be improved. The U.S. Army Weapons and Equipment Research and Engineering Center (ARDEC) and Nalas Engineering Service Co., Ltd. used RAM technology to prepare hexanitro-hexaazaisowurtzitane (CL-20) eutectic explosive. CL-20/HMX eutectic explosive was prepared by adding 2- propanol/acetonitrile into a certain proportion of CL-20 and octogen [18]. Although the sensitivity of this eutectic explosive is higher than that of pure CL-20, it is found that the process of preparing eutectic explosive by this RAM technology is safe and conducive to scale-up. Subsequently, ARDEC and Nalas Engineering Service Co., Ltd. prepared a eutectic explosive with the molar ratio of 1- methyl-3,5-dinitro-1,2,4-triazole (MDNT) to CL-20 of 1:1 by using RAM technology. The sensitivity of this eutectic explosive is equivalent to that of CL-20, but it also failed to improve the sensitivity of CL-20 [19-20].

Three kinds of CL-20-based eutectic materials, CL-20/2- hydrophobic-1-methylimidazole, CL-20/4- methyl -5- nitroimidazole and CL-20/ caprolactam, were prepared by Xi 'an Institute of Modern Chemistry by acoustic resonance technology. The solvent used in preparing these eutectic materials is the same as that used by solution evaporation method, and it is not necessary to replace/screen the solvent again. After testing, the eutectic materials prepared by acoustic resonance technology have different particle sizes and irregular shapes. Compared with CL-20, the exothermic peak temperatures of three kinds of CL-20 eutectic are all decreased, and the pyrolysis process, heat release, the melting peak temperature of eutectic molecules combined with CL-20, the initial pyrolysis temperature and other characteristic parameters are related. Compared with CL-20, the eutectic materials of CL-20/4- methyl -5- nitroimidazole have faster pyrolysis rate and greater heat release, and CO_2 and H_2O in the pyrolysis products increase obviously after eutectic. After CL-20 eutectic, the ignition delay time and flame propagation characteristics have obviously changed. The CL-20/ caprolactam eutectic material with higher carbon content burns more completely, the flame is brighter and the strength is higher [21].

4.1.2. Friction Sensitivity Participate in the Preparation of RDX Spherulites

North University of ChinaandXi 'an Institute of Modern ChemistryA method of preparing RDX spherulites by acoustic resonance assisted solvent erosion technology was designed. Based on the traditional solvent erosion crystallization technology, the original paddle stirring was replaced by acoustic resonance. Under the coupling effect of vibration macro-mixing and acoustic micro-mixing, explosive crystals and solvent system were in a dynamic crystallization balance. Under the constant erosion of solvent fluid, the edges and corners of explosive crystals gradually became smooth, and finally RDX spherulites were prepared. This technology realizes the whole paddle-free mixing in the real sense. On the one hand, it improves the safety of the process and avoids the crystal breakage caused by the collision between blades and particles. On the other hand, the shear force field tends to be consistent, which is conducive to obtaining high uniformity explosive particles. In addition, the vibration frequency is close to the material characteristics, which can produce better synergistic effect and improve the spheroidization efficiency of explosive particles [22].

4.1.3. Friction Sensitivity Participate in the Enhanced Reaction Synthesis

Xi 'an Institute of Modern Chemistry used acoustic resonance to enhance the debenzylation of hexabenzyl hexaazaisowurtzitane (HBlW) to synthesize tetraacetyldibenzyl hexaazaisowurtzitane (TADB). Under suitable process conditions, compared with the traditional kettle process, the TADB yield of acoustic resonance enhanced reaction is unchanged, the reaction time is shortened to 90min, the time is shortened by 91.7%, and the reaction pressure can be effectively reduced to 0.1MPa [23].

Li Bindong of Nanjing University of Science and Technology combined microfluidic and acoustic resonance technology to design and build a continuous flow acoustic resonance hybrid platform for nano-recrystallization of TATB. Without acoustic resonance technology, the PSD of TATB particles obtained by microfluidic recrystallization ranges from 45.8 nm to 1036.9 nm, with an average of 159.8nm；. After acoustic resonance, the PSD is narrowed to 14.1～111.5nm, with an average of 50． 8nm, and the crystal size is more uniform and smaller [24].

4.2. Application of Acoustic Resonance Mixing Technology in Energetic Materials Processing

4.2.1. Participate in Processing Propellant

In 2010, POURPOINT, an American scholar, used RAM technology to mix aluminum/ice propellant, which was tested on the American ALICE missile and successfully launched [25]. In 2012, the United States evaluated the feasibility of RAM processing propellant at the military base in Lake China, California. Through the performance comparison test of AP/Al-based propellant bonded with hydroxyl caprolactone modified polyether (HTCE) by RAM processing and Baker-Perkins(BP) vertical mixing processing, it was found that the materials mixed by acoustic resonance have higher uniformity, and the safety of the propellants obtained by the two processes is basically the same, and the burning rate is the same at low pressure, and at high pressure [9,26]. In the same year, Digital Solid Propellant Co., Ltd. of the United States carried out a 5 gallon (about 20L) scale-up test of HTPB bonded propellant by using RAM5 acoustic resonance mixer of ResoDyn Company. The results showed that scale-up could obviously save mixing time and cost [27]. In 2013, American scholar REESE and others used an acoustic resonance mixer to mix a new type of nitrate composite propellant. The mass fraction of each material in the formula was: SMX83%, aluminum powder 2%,HTPB11.15%, isokui nonanoate 2.23%,MDI1.62%, and the mixing time was 10 min. Based on the study of its mixed properties, the author thinks that SMX-HTP propellant can supplement or replace AP as the next generation solid rocket propellant from the aspects of propellant performance, processing, safety and combustion performance [28]. In 2020, the National Institute of Applied Science (TNO) of the Netherlands reported the comparative experimental study between RAM technology and conventional mechanical mixing processing. The results showed that the oxidant particles in the propellant obtained by the two processing methods and their uniformity, density and burning rate were completely the same [29].

Based on the surface modification of Al particles, the Key Laboratory of Combustion Thermal Structure and Internal Flow Field of Northwestern Polytechnical University successfully prepared multi-scale interface adjustable semi-embedded Al/RDX and fully embedded Al@RDX composite particles by acoustic resonance and spray drying techniques. Compared with the traditional mechanical mixture, the density of composite particles remained basically unchanged, but the combustion heat increased to 17.31kJ/g and 18.8kJ/g respectively. The DSC results show that both methods can improve the thermal decomposition heat of RDX and improve the thermal stability. The gas phase decomposition products of RDX were not changed by aluminum powder embedding, but the relative content of HCHO increased: the first decomposition stage of RDX was transformed from two-dimensional nucleation growth model (A2) to chain fracture model (L2); the second decomposition stage of fully embedded Al@RDX was transformed into autocatalytic model (AC) [30].

According to the characteristics of acoustic resonance mixing technology, Hubei Institute of Aerospace Chemistry used SEM3 acoustic resonance mixer to study the effects of technological parameters such as different feeding amount and mixing time on the safety, combustion, mechanics and technological properties of NEPE propellant, and compared it with the performance of propellant prepared by vertical mixer. The results show that the impact sensitivity, friction sensitivity and electrostatic discharge sensitivity of propellant slurry prepared by vertical mixing are equivalent to the safety performance of propellant slurry prepared by vertical mixing. The measured density of the propellant prepared at different feed rates of 500 g, 800 g and 1000g is basically the same as that prepared by vertical mixing, which shows that the acoustic resonance mixing process can effectively mix the propellant slurry. The burning rate of 7MPa propellant is 0.14 ~ 0.22 mm/s lower than that prepared by vertical mixing, and the maximum tensile strength at 20℃, 70℃ and -30℃ is obviously lower than the mechanical properties of propellant prepared by vertical mixing [31].

4.2.2. Participate in Processing PBX

QinetiQ Company of the United Kingdom conducted a comparative experimental study between acoustic resonance mixing and conventional planetary stirring mixing for cast-cured PBX bonded with HTPB. The results showed that acoustic resonance mixing had no effect on dispersion, and the curing effect was better, but there was a slight difference in modulus, and the influence on performance was almost negligible [32-33]. BAE Systems, UK, studied the processing of RDX/HTPB shaped charge by using RAM technology. The results show that RAM technology can obtain dense PBX, and its detonation performance is the same as that obtained by traditional hybrid method [34]. In fact, acoustic resonance processing only needs a thin splash-proof cover, so that the container with the same volume can be filled with more explosives, which is especially suitable for the processing of shaped charges.

Xi 'an Institute of Modern Chemistry conducted an experimental study on the uniformity and process safety of acoustic resonance mixing of PBX explosives with solid content of 86% and 90% respectively through the prototype of acoustic resonance mixing test [35-36]. The experimental magnitude is 150g and 300g respectively. The results show that the mixing effect of RAM technology is very good, and the materials can be evenly mixed in 1000s and 1200s respectively. The process safety is good, the electrostatic voltage is almost zero during the mixing process, and the friction heat generation speed of the material is much lower than the heat loss of the material to the outside. It is proved that the acoustic resonance mixing process is feasible for the whole field mixing of explosives with medium solid mass fraction.

4.3. Application of Acoustic Resonance Mixing Technology in In-situ Charging

The Institute of Chemical Materials of China Academy of Engineering Physics has designed an acoustic resonance in-situ charging method for casting PBX [37]. Firstly, the warhead shell is expanded in capacity, explosives and binders are added into the warhead shell with expanded capacity, then solvent is added for wetting, the warhead shell filled with materials is fixed as a whole on the acoustic resonance table, and the acoustic resonance equipment is started. After the materials are fully and uniformly mixed,

ISSN 2616-5767 Vol.8, Issue 2: 90-95, DOI: 10.25236/AJETS.2025.080212

the solvent in the materials is removed by vacuum treatment under the vibration state, and after the Resonant Acoustic Mixing charging process, the expanded part of the shell is removed by cutting the riser to obtain a fully filled charge. This method uses acoustic resonance technology to realize explosive mixing and in-situ charge molding in the shell, and one process can replace the two processes of mixing and pouring to realize one-time mixed charge molding of the shell of special-shaped warhead.

5. Conclusion

As a new hybrid technology, acoustic resonance has the following advantages:

(1) Acoustic resonance mixing technology does not need paddles and screws used in traditional mixing technology, which reduces the force stimulation and thermal stimulation, improves the safety in the mixing process, and is very suitable for mixing energetic materials sensitive to stimulation.

(2) As a whole-field mixing technology, acoustic resonance mixing technology greatly improves the mixing efficiency compared with the traditional technology, and can produce strong mixing effect with less energy input. In a large number of experiments and production, acoustic resonance technology can effectively shorten the mixing time and improve the production efficiency.

(3) Acoustic resonance mixing technology can be widely adapted to various mixed material systems (such as solid-solid, solid-liquid, liquid-liquid, gas-liquid, etc.), and the steps that need to be mixed in experiment and production can be replaced by acoustic resonance mixing.

Compared with traditional mixing methods, acoustic resonance mixing has many advantages. The research on acoustic resonance mixing and the research and development of acoustic resonance mixing equipment in China have also been going on, and some achievements have been made. The application of acoustic resonance hybrid technology to the practical production of energetic materials and other civil fields will be the focus of the next work.

References

[1] Harold W, Jeremiah J, Scott L, et al. Apparatus and method for resonant vibratory mixing:US7188993 [P]. 2007-03-13.
[2] Zhan Xiaobin, Tang Ying, Lan Changyi, et al. Dynamic characteristics and performance analysis of three-mass acoustic resonance mixer [J]. Vibration and impact, 2020,39(2):204-208.
[3] https://resodynmixers.com. 2025-02-01.
[4] Zhang Yiming, Ma Ning, Wang Xiaopeng, et al. Numerical simulation of solid-liquid two-phase resonance mixing [J]. Progress of Chemical Industry, 2018,37(3):913-919.
[5] Osorio J, Muzzio F. Evaluation of resonant acoustic mixing performance [J]. Powder Technology, 2015,278:46-56.
[6] Peter L. Resonant acoustic mixing principals and analysis [C]// Resonant Acoustic Mixer Energetic Conference, Resodyn head office in Butte, Montana,14 July 2011.
[7] Davey R J，Wilgeroth J M，Burn A O. New Age of PBX Manu- facturing: Optimisation of RAM[C]//49th International Annual Conference of the Fraunhofer ICT, Karlsruhe, Germany, June 25 - June 28,2018:123
[8] Ma Ning, Chen Song, Jiang Haolong, et al. Experimental study on acoustic resonance mixing of highly viscous explosives simulators [J]. Guangzhou Chemical Industry, 2015,(19):46-48,63.
[9] Cross T A, Nelson A P, Ferguson B P. Processing Benefits of Resonance Acoustic Mixing on High Performance Propellants and Explosives [C]// 38th International Pyrotechnics Seminar, Denver, CO, USA, 10-15 June 2012:190-206.
[10] Coguill S, Martineau Z, Martineau ZR. Vessel Geometry and Fluid Properties Influencing Mix Behavior for Resonant Acoustic Mixing Processes [C]// 38th Inter- national Pyrotechnics Seminar, Denver, CO, USA, 10-15 June 2012:116-119.
[11] Qu Yue, Yi Wenjun, Guan Jun. Study on the production efficiency of acoustic resonance mixing optimization of explosives and explosives [J]. Journal of Weapon Equipment Engineering, 2018,39(8):58-62.
[12] Zhu Shifu, Wang Xiaopeng, Chen Song, et al. Numerical simulation of dispersion characteristics of resonance sound at low solid content [J]. Progress of chemical industry, 2019,38(10):4414-4422.
[13] Ma Ning, Zhang Zhe, Sun Xiaopeng, et al. Study on the variation law of resonant sound mixing process of plastic bonded explosive simulators [J]. Journal of Military Engineering, 2019,40(12):2440-2446.

[14] Li Ya, Yi Qingfeng, Jiang Jianhong, et al. Paddle-free mixing technology of lining slurry [J]. Solid rocket technology, 2019,42(2):234-238.
[15] Ma Ning. New development of acoustic resonance hybrid technology in China [J]. Journal of Explosives, 2023,46(9).
[16] https://www.ramixers.com/2025-02-01.
[17] https://www.hamixer.com/gsjs.html 2025-02-01.
[18] Stephen R Anderson, David J am Ende, Jerry S Salan, et al. Preparation of an Energetic-Energetic Cocrystal using Resonant Acoustic Mixing [J]. Propellants, Explosives, Pyrotechnics, 2014,39(5):637-640.
[19] Stephen R Anderson, Pascal Dubé, Mariusz Krawiec, et al. Promising CL-20-based energetic material by cocrystallization [J].Propellants, Explosives, Pyrotechnics, 2016,41:783-788.
[20] Stephen R Anderson, Pascal Dubé, Mariusz Krawiec,et al. CL-20:DNMT cocrystal crystal structure [P]. US Parent: US2015/0361056.
[21] Li Haijian, Chen Chao, Zhang Zhe, et al. Preparation and pyrolysis of CL-20 based eutectic materials based on acoustic resonance technology [J]. Journal of Explosives, 2022,45(6):848-855.
[22] North university of china, Xi 'an Institute of Modern Chemistry. A method for preparing RDX spherulites by acoustic resonance assisted solvent erosion technology: CN202111395698.8[P]. 2022-03-25.
[23] Tang Xiaofei, Zhang Yao, Lian Peng, et al. Hydrodebenzylation of HBIW enhanced by acoustic resonance to synthesize TADB [J]. Journal of Explosives, 2022,45(5):639-644.
[24] Song Zhang, Lewu Zhan, Yifan Zhang, Jing Hou, Bindong Li, Continuous flow resonance acoustic mixing technology: a novel and efficient strategy for preparation of nano energetic materials[J]. Fire Phys Chem, Volume 3, Issue 1,2023:29-36,
[25] TIMOTHEE L. POURPOINT, TYLER D. WOOD, MARK A. PFEIL, et al. Feasibility Study and Demonstration of an Aluminum and Ice Solid Propellant [J]. International journal of aerospace engineering,2012,874076.1-874076.11.
[26] Andrew Nelson, Tara Cross. Processing benefits of resonance acoustic mixing on high performance propellants and explosives [R]. ADA597433,2012.
[27] McPherson M D. Process and formulation development of cast- able energetic formulations using the LabRAM and RAM5 Mixer [C]// 38th International Pyrotechnics Seminar，Denver, CO, USA, 10-15 June 2012:1-16.
[28] REESE D A, GROVEN L J, S F SON. A new nitrate ester composite propellant [C]// 5th European Conference for Aeronautics and Space Sciences(Eucass), 2013.
[29] Martijn Zebregs, Alfons E H J. Mayer, and Antoine E.D.M.vander Heijden. Comparison of propellant processing by cast-cure and resonant acoustic mixing [J]. Propellants, Explosives, Pyrotechnics, 2020,45:87-91.
[30] Xu Ruixuan, Xu Jiaxing, Xue Zhihua, et al. Preparation and thermal decomposition characteristics of multi-scale interface-adjustable Al-RDX energetic composite [J]. Journal of Military Engineering, 2023,44(3):691-701.
[31] Pan Xinzhou, Lu Zhimeng, Wang Xiaoying, et al. Preliminary application of acoustic resonance mixing in the preparation of NEPE propellant [J]. Solid rocket technology, 2022,45(2):269-273.
[32] Joran Homan, Simon Torry, Peter Gould, et al Using reso- nant acoustic ™ mixer for mixing inert material [C]// 47th Inter- national Annual Conference of the Fraunhofer ICT, Karlsruhe, Germany, June 28-July 1, 2016:52.
[33] Homan J, Sory D, Tod D, et al. A comparison of the dynamic mechanical properties of explosive simulants prepared using traditional and resonant acoustic mixing [C]// New Trends in Research of Energetic Materials, Czech Republic, 2018:147-157.
[34] James M Wilgeroth，Rosie J Davey，Andrew O Burn. Resonant, in-case mixing of a polymerbonded explosive shaped charge[C]// 49th International Annual Conference of the Fraunhofer ICT, Karlsruhe, Germany, June 25-June 28, 2018:28.
[35] Ma Ning, Qin Neng, Jiang Haolong, et al. Experimental study on acoustic resonance mixing of PBX explosives [J]. Blasting Equipment, 2016,45(4):26-29.
[36] Ma Ning, Chen Song, Zhang Zhe, et al. Experimental study on resonance sound mixing of PBX explosives II [J]. Blasting Equipment, 2017,46(6):1-5.
[37] Institute of Chemical Materials, China Academy of Engineering Physics. An acoustic resonance in-situ charging method suitable for casting PBX:CN202210212326.5 [P]. 2022-06-07.