Research Article

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Design and Principal Analysis of Automated Multi-Specification Target Pneumatic Rabbit System for Isotope Production Line

J.J. Bao[1*], J.Y. Liu[2], Z. Liu[3], T.J. Zhang[4], C.Y. Liu[5] & P.F. Zhang[6]

[1]*China Institute of Atomic Energy, Beijing 102413, China*
[2]*Chengdu Cyclotron Science and Technology Co, Ltd, China*
[3]*CNNC Engineering Research Center of Accelerators, Beijing, China*

[*]**Corresponding author:** J.J. Bao, China Institute of Atomic Energy, Beijing 102413, China.

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Abstract
In medical isotope production, target materials for different isotopes exhibit significantly different phys-ical properties. To improve nuclear reaction yield and efficiency, target structures of various specifications are required to produce different radioisotopes. However, multi-specification targets hinder automat-ed production and increase on-site operation time. To reduce personnel radiation exposure risk in high-radiation environments, enhance rabbit system auto-mation, and improve target specification universality, this study designs a complete automated multi-specification pneumatic rabbit system. A dual-specification target rabbit box is designed using a multi-gear buckle device. Segmented pneumatic transmission simulations verify system design ration-ality, and pipeline parameters and control processes are determined. The system enables bidirectional pneumatic transmission, precise positioning, and automated operation, providing a new solution for safe and efficient medical radionuclide production.

Keywords: 50 MeV, Beam Transport Line, Large Spot, High Uniformity, Scanning Magnet.

Introduction

Medical radionuclides are irreplaceable in nuclear medicine diagnosis and treatment. Cyclotron solid target technology is a key platform for national stra-tegic research in nuclear medicine, life sciences, and related fields. Per the Medium- and Long-Term De-velopment Plan for Medical Isotopes (2021-2035), the national strategic significance of developing key medical radionuclides like Zr-89 is increasingly prominent [1].

As one of the most widely used equipment for com-mercial medical isotope raw material production, multi-particle superconducting cyclotrons can pro-duce multiple medical isotopes [2]. The significant differences in physical properties of various medical isotopes require different target structure designs and fixing methods for different radionuclide production, necessitating targets with different sizes and shapes [3]. Additionally, in actual production, to meet auto-mated target loading requirements, specific front-back orientation of targets must be ensured when entering the target chamber. Therefore, a target ori-entation identification system needs to be configured after targets enter the irradiation station. To achieve flexible production of multiple radionuclides and adapt to different irradiation process parameters, it is urgent to develop a pneumatic rabbit transmission system capable of automatically identifying and ad-justing the posture of multi-specification targets in loading-unloading devices [4, 5].

In medical radionuclide production, the pneumatic rabbit system connects the cyclotron irradiation sta-tion and hot cell, responsible for fast, safe transmis-sion of solid targets pre- and post-irradiation. Pneu-matic rabbit systems have been widely applied across multiple fields: in reactors for rapid sample irradia-tion and neutron activation analysis, with the Munich Research Reactor's automated system having operat-ed successfully for years; in modern hospitals for transporting blood samples and pharmaceuticals; in industrial laboratories for rapid quality control sample testing; and in the mining industry for transport-ing ore and waste materials, where the pneumatic capsule pipeline system at Japan's Karasawa Lime-stone Mine has transported over 62 million tons of limestone since its commissioning in 1980[6,7].

These applications fully demonstrate the unique ad-vantages of pneumatic transmission technology [8].

Existing rabbit systems have three key limitations:

1. Poor target specification adaptability—traditional rabbit boxes only carry single-specification targets, limitng production flexibility;
2. Low automation—manual loading is common in China, reducing efficiency and increasing radiation exposure risk;
3. Lack of automatic identification, preventing recognition of different-specification targets.

To address these issues, this study designs an auto-mated multi-specification rabbit system capable of automated transmission, automatic identification, and automated operation of multi-specification targets, providing a new solution for safe and efficient medi-cal isotope production.

Design of The Rabbit System

System Scheme

The system mainly comprises an air supply system, hot cell end interface, irradiation station end inter-face, transmission pipeline system, rabbit box, and automatic control system. The rabbit pipeline is de-signed per irradiation station/hot cell layout (see Fig. 1).

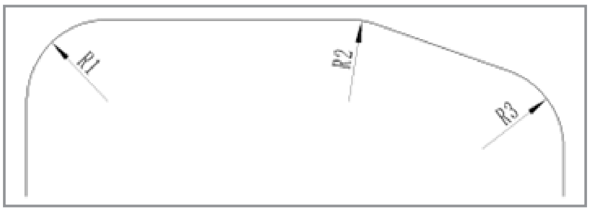

Figure 1: Pipeline Layout Diagram.

Key Component Design

Rabbit Box Design

As the core carrier container of the transmission system, the rabbit box can transport targets of dif-ferent specifications. The rabbit box structure is shown in Figure 2(see Fig. 2). The rabbit box adopts a tubular box structure with dimensions of φ47mm×63mm; made of aluminum; its upper end is closed, and the lower end is equipped with a magnetically attached opening-closing cover; the box wall thickness design ensures adequate struc-tural strength under pneumatic transmission pressure; an annular groove is set in the middle section of the box body to facilitate reliable clamping by external clamping devices. The magnetically at-tached opening-closing cover connects to the box body via magnetic strips; the magnetic force design ensures reliable sealing during transmission while facilitating automated operation.

A push-pull drawer mechanism is installed inside the rabbit box. The main body of this structure is a high-strength rectangular support plate. Its push-pull direction is set along the axial direction of the rabbit box; buckle grooves can be set on both the front and back of the middle support plate to fix different-specification targets, achieving multi-specification design. The multi-gear buckle device allows the front and back of the middle support plate to be configured with same or different speci-fication buckle grooves as needed, capable of fixing multiple small targets.

For precise positioning and automatic identification, the system adopts a reflective optical positioning scheme. Corner reflectors for large and small tar-gets are installed at 180-degree symmetric positions on both sides of the high-strength rectangular support plate. A laser ranging sensor fixedly installed at the irradiation station end emits laser pulses that reflect back via the corner reflectors, calculating the support plate rotation position by analyzing reflec-tion signal time and intensity. The sensor continu-ously scans during drawer extraction, and when the corner reflector enters the scanning range, the con-trol system rotates the drawer to the optimal grasp-ing angle and sends positioning completion signals to the robotic arm.

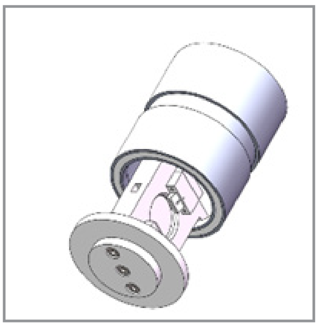

Figure 2: Rabbit Box Structure Diagram.

Pneumatic Transmission Simulation and Pipeline Design

Computational Fluid Dynamics (CFD) is used for hydrodynamic analysis of key transmission segments. Three-dimensional simulation models of the rabbit box in horizontal, vertical, and turning pipeline segments are established. The inlet is set with an air velocity of 15 m/s, and the outlet adopts pressure outlet boundary conditions.

To ensure continuous and stable transmission of the rabbit box, the system working air velocity must be greater than the critical transmission velocity. According to gas-solid two-phase flow theory, the critical transmission velocity can be calculated by Formula 1 [7].

$$U_t = \sqrt{\frac{8mg}{\pi D^2 \rho_g} \cdot \left[\left(\frac{D^2}{D^2 - d^2}\right)^2 - 1\right]} \quad (1)$$

After calculation, the system design inlet air velocity of 15 m/s is greater than the critical air velocity and meets transmission requirements.

To determine the optimal gap between the rabbit box and pipeline, simulations were conducted for three unilateral gaps: 1.7mm, 2.0mm, and 2.3mm (see Fig. 3). Results show that smaller gaps produce greater acceleration, but excessively small gaps increase processing difficulty. Considering transmission efficiency and manufacturing cost comprehensively, a unilateral gap of 2.0mm was determined. Under this parameter, the rabbit box can accelerate to 5 m/s in horizontal segments, and although vertical segments need to overcome self-weight, transmission is smooth.

Pipeline Wall Thickness Design: According to ASME B31.3 standard, pipeline wall thickness is calculated by Formula 2.

$$t = \frac{PD}{2SE + PY} + C \qquad (2)$$

The calculated theoretical wall thickness is 2.1mm. Considering safety factor and standard pipe specifications, φ57mm×3mm stainless steel seamless pipe is selected.

Bend Radius Design: According to rabbit box dimensions and referencing pipeline engineering experience, the minimum bending radius for rigid carriers is typically 2-2.5 times the pipe outer diameter. Pneumatic conveying research indicates that within an R/D ratio range of 4.5-20, larger ratios help reduce pressure drop and wear. Comprehensively considering geometric constraints and transmission performance, a pipeline bend radius of R=600mm is selected. CFD simulation verification shows that under this bend radius, the rabbit box can smoothly pass through bent pipe segments, and pressure drop and velocity distribution meet requirements [8].

The actual system total transmission distance is approximately 15m, with a unilateral gap of 2.0mm between pipeline and rabbit box. Both straight and bent pipe segments use φ57mm×3mm stainless steel pipe, with bent segment bend radius R≥600mm.

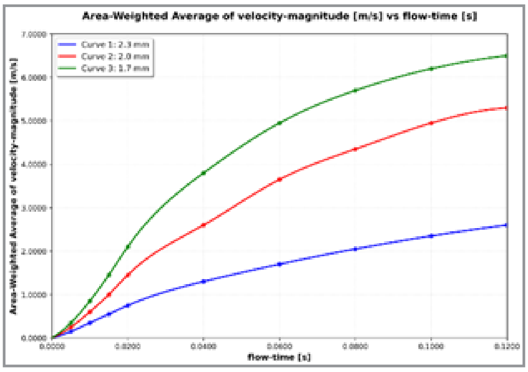

Figure 3: Gap Simulation Comparison.

Hot Cell End and Irradiation Station End Load-ing-Unloading Device Design

The structures of the hot cell end and irradiation station end loading-unloading devices are basically identical, mainly consisting of a loader mechanism, lifting platform mechanism, cylinder clamping-rotating mechanism, and side clamping mechanism. The loader mechanism comprises a lifting cylinder, lower flange, sealing ring, guide shaft, upper flange, loading pipe, and other components. The rabbit box is placed on the lower flange, and after the cylinder rises, a sealed cavity is formed. Compressed air is introduced to push the rabbit box into the pipeline for transmission.

The lifting platform mechanism adopts a motor-driven precision lifting mechanism capable of pre-cise vertical positioning of the rabbit box. The lift-ing platform stroke is designed based on operational requirements. The cylinder clamping-rotating mechanism is integrally mounted on the lifting platform mechanism, including clamping compo-nents and rotation drive mechanism, used to clamp the rabbit box cover and achieve precise positioning of different-specification targets through rotation. Its rotation angle can be precisely controlled.

The side clamping mechanism is positioned outside the loader. When the lifting platform descends to align the rabbit box middle annular groove with the external clamping mechanism, the clamping mech-anism automatically clamps the middle annular groove of the rabbit box to fix the rabbit box shell, ensuring that when the lifting platform continues descending, the magnetically attached opening-closing cover can smoothly separate from the rabbit box shell, and the drawer mechanism is reliably pulled out.

Pneumatic Circuit Design

The pneumatic circuit adopts bidirectional control to achieve rabbit box reciprocating transmission. Compressed air is supplied by an air compressor, stabilized to 0.3MPa through an air storage tank, and enters the transmission pipeline after ad-just-ment by a pressure reducing valve. The pneumatic control system is shown in Figure 4(see Fig. 4).

Forward Transmission Process: After the PLC re-ceives instructions and detects pipeline status, it controls the hot cell end electromagnetic direction-al valve to switch to the working position for air supply, while the irradiation station end electro-magnetic valve synchronously switches to the ex-haust position. The speed control valve regulates airflow to maintain stable transmission. After the position sensor monitors the rabbit box arrival at the irradiation station end, the PLC closes the hot cell end electromagnetic valve to complete trans-mission.

Reverse Transmission Process: The irradiation sta-tion end electromagnetic valve switches to the working position for air supply, while the hot cell end switches to the exhaust position. The PLC automatically completes control switching based on position feedback. The exhaust end is equipped with silencers to reduce noise. Pneumatic pipelines use PU material, and pneumatic components use aluminum alloy material.

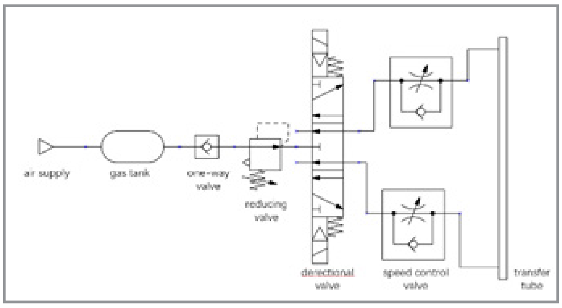

Figure 4: Pneumatic Control Diagram.

Control Process Design

Automatic Control System Design

The automatic control system uses a Programmable Logic Controller (PLC) to achieve automated rabbit box conveying operations, integrating sensor detec-tion, pneumatic transmission control, and other func-tional modules.

The system adopts a dual-layer clamping strategy: the cylinder clamping-rotating mechanism clamps the magnetically attached opening-closing cover at the bottom of the rabbit box. When the lifting plat-form descends to align the rabbit box middle annular groove with the side clamping mechanism, the side clamping mechanism automatically clamps the annu-lar groove to fix the box shell. The lifting platform continues descending, pulling down the magnetically attached opening-closing cover through the cylinder clamping mechanism to pull out the drawer-type target support structure from the tubular box.

After the drawer mechanism is fully pulled out, the cylinder rotating mechanism initiates rotation. The PLC selects the corresponding position sensor based on the preset target type signal and monitors rotation angle in real time. When the target rotates to the optimal grasping angle for the robotic arm, it sends a positioning completion signal to the PLC. The rotat-ing mechanism stops and locks. After the system verifies the sensor signal to ensure precise target alignment, it sends coordinate information to the robotic arm to complete automatic grasping.

Additionally, the system has position detection, air-flow regulation, historical data recording, fault alarm, and other functions. All operations have pre-set conditions and interlocked actions to ensure safe-ty.

Irradiation Station End Working Process

Example: Irradiation station end receives a large Zr-89 target:
Reception: Load the large target at the hot cell end—send target type signal to the PLC (records signal and selects rotation positioning sensor type). Pneumatically transport the box to the irradiation station end's lifting platform;
Clamping: The lifting platform's cylinder clamping-rotating mechanism clamps the box's lower magneti-cally attached cover;
First descent: The platform descends to align the box's annular groove with the external clamp—external clamp clamps the groove;
Separation: The platform continues descending, separating the cover from the box shell; pull out the drawer;
Positioning: The platform descends to a preset posi-tion (exposes the entire target). The drawer bottom locks with the box shell—platform stops;
Rotation Positioning: The clamping-rotating mech-anism drives drawer rotation. The PLC activates the large-target sensor (per recorded signal). When the tar-get rotates to face the robotic arm, the sensor sends a positioning signal—rotation stops;
Precise Positioning: Reconfirm sensor signal to ensure target alignment with retrieval position;
Automatic Retrieval: Robotic arm retrieves the target per sensor feedback;
Return: Reverse operation for box transmission from irradiation station to hot cell.

Small Target Loading Process

The process is identical to large targets, except for reception and rotation positioning stages. Multiple small targets can be loaded simultaneously; the small-target sensor enables sequential precise posi-tioning and retrieval.

Conclusion

This study designs a multi-gear buckle device for dual-specification target transmission in the automat-ed multi-specification pneumatic rabbit system. Combining the magnetically attached cover with the lifting platform and cylinder clamping-rotating mechanism achieves automatic target identification and precise positioning. Formula calculation and CFD simulations verify pneumatic transmission fea-sibility, and pipeline parameters/control strategies are determined.

The system enables bidirectional pneumatic trans-mission, multi-specification automatic identification, and precise positioning. It improves automation and target universality, reduces personnel radiation expo-sure, and meets safety/efficiency requirements for mass production of medical radionuclides like Zr-89.

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