# Research on the design, development and manufacturing key technologies of double-layer four-mold tire curing press

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**Abstract:** This article primarily investigates the application of a double-layer four-mold tire curing press in the curing of semi-steel radial tires. Double-layer four-mold curing refers to the synchronous control of four molds on one curing press. The research results indicate that, compared to traditional single-layer dual-mold curing presses, this double-layer four-mold tire curing press reduces equipment footprint by 41%, increases production capacity by 180% compared to single-layer dual-mold, and reduces energy consumption per tire by 22%.

**Key words:** semi-steel radial tire; four-mold vulcanization; double-layer vulcanization

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The current tire industry faces the triple demands of "improving quality, reducing costs, and increasing efficiency": on the one hand, high-end tires require higher precision in curing (such as pattern clarity and carcass uniformity), which is difficult to achieve with the traditional single-layer curing press temperature control error (±2.5 ℃; on the other hand, the cost of workshop land is rising, and the contradiction between the "large footprint and low capacity" of single-layer equipment becomes prominent (a single dual-mold curing press covers an area of 36 $m^2$, including the post-inflation device, and with a curing time of 11.5 minutes per tire, the daily average capacity is about 250 tires). The dual-layer quad-mold curing press, with its innovative layout of "upper and lower dual layers + dual molds on each layer", can achieve "nearly unchanged footprint and nearly doubled capacity". The daily output of cured tires can reach around 450, but it requires overcoming three major technical difficulties and bottlenecks:

Difficulties and bottlenecks in structural stability: The dual-layer layout results in complex stress on the frame, which is prone to deformation or vibration transmission, affecting vulcanization accuracy.

Challenges and bottlenecks in synchronous control: The four sets of molds (double-layer, four-mold) require synchronous mold opening and closing, temperature control, and pressure application, which are more difficult to control compared to the traditional single-layer, dual-mold control logic.

Challenges and bottlenecks in maintenance convenience: The upper mold is high off the ground and has limited space, making it difficult to conduct maintenance and mold changes in the later stages.

To address the industry pain points of traditional single-layer dual-mold curing presses, such as low productivity, large footprint, and high energy consumption, this paper takes the double-layer quad-mold tire curing press as the research object and systematically conducts technical research and development throughout the entire design, research, and manufacturing process.

Through the verification of 3D modeling (SolidWorks), finite element simulation, and industrial manufacturing, we have broken through core technologies such as force balance

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of double-layer structure, four-mode synchronous control, efficient temperature control, and precision manufacturing, and developed vulcanization equipment suitable for 12"~17" passenger car tires.

After six months of industrial application and production, the curing pass rate has stabilized at 99.7%, providing key equipment support for the large-scale and green production of the tire industry, as well as theoretical and practical references for the technological upgrading of multi-mode curing presses.

Focusing on the aforementioned bottlenecks, this paper constructs an integrated technical solution encompassing "design-simulation-manufacturing-verification" to facilitate the industrialization and implementation of the equipment.

## 1 Core design technology of double-layer four-mold tire curing press

### 1.1 Overall layout and structural optimization of double-layer four-mode

#### 1.1.1 Spatial layout and interference avoidance analysis

The design adopts a "symmetrical double-layer frame": the center-to-center distance between the upper and lower molds is set at 2,060 mm, and the horizontal spacing between two sets of molds on each layer is 840 mm. The mold opening and closing trajectory is simulated through SolidWorks motion simulation, with the upper and middle layers opening and closing simultaneously. The middle layer has a closing stroke of 1,400 mm, and the oil cylinder is Φ100 with a speed of 7s/time. The upper layer has a closing stroke of 2,570 mm, and the oil cylinder is Φ100 with a speed of 13s/time, ensuring no mechanical interference between the upper and lower layers or the left and right molds. The frame is made of Q355 high-strength steel structural components, and the mold opening and closing guide adopts linear guide rails HGW-55CB, with two linear guide rails on each side. The mold clamping adopts a cylindrical structure, inserted laterally into the preset empty spaces on both sides of the frame. The cylindrical mold clamping is treated with 45# quenched and tempered material, with dimensions of Φ120×400 mm. The frame lock hole adopts an egg-shaped hole shape, set upright to facilitate the insertion of the cylindrical lock head. The mold opening position of the middle and upper layers is locked, and the frame lock hole adopts a round hole structure, with the lock head in the form of a cylindrical structure. The mold clamping oil cylinder is placed on a fixed base, and each set of main mold clamping oil cylinder adopts a size of Φ180×500 mm×4, with a maximum mold clamping force of 1,900 KN. Due to the design using a frame-type frame and the mold adopting a stacked design, the material usage is reduced by 25%, and the overall weight is reduced to 32t (about 23% lighter than traditional equipment with the same production capacity).

#### 1.1.2 Force balance and vibration control

Perform static and dynamic force simulation analysis based on finite element method

Statics simulation: During full-load vulcanization (with four molds maintaining pressure at 16 MPa simultaneously), the maximum deformation of the frame is ≤0.12 mm, the stress value in the stress concentration area (at the locking pin hole) is ≤160 MPa (Q355 yield strength is 345 MPa), and the safety factor is ≥2.15.

Kinetic simulation: Under the impact condition of mold opening and closing, the vibration amplitude of the equipment is controlled within 0.05 mm by using a "rubber buffer pad" (with a rubber hardness of 80 Shore A) at the bottom of the lower mold, to prevent vibration transmission from causing displacement of the upper mold.

### 1.2 Research and development of four-mode synchronous control technology

#### 1.2.1 Synchronous clamping and mold opening and closing system

Adopting a composite control scheme of "total hydraulic drive + sub-servo adjustment"

Main oil circuit: Hydraulic power is provided by a hydraulic pump driven by one 5.5 kW and one 37 kW servo motors, ensuring stable output of clamping force for four molds (with a fluctuation of ±5 kN); and controlling operational actions.

Servo adjustment: Each set of middle and upper molds is equipped with an independent lifting cylinder device, controlled and powered by a servo motor, featuring fast action time and quick response speed (response time ≤50 ms). The PLC corrects the speed and flow of the servo motor in real-time based on the analog PID algorithm, achieving a synchronous error of ≤0.5 mm in mold opening and closing for four molds

(the synchronous error of traditional equipment is ≥2 mm).

The left and right upper and lower molds are controlled by separate hydraulic cylinders and servo systems, ensuring synchronous operation of the upper and lower mold opening and closing, which greatly saves time in mold opening and closing (saving 3~4 seconds in mold opening and closing time) and improves production efficiency.

### 1.2.2 Four-mode synchronous temperature control system

Establish a three-level temperature control system featuring "central heating + temperature control by different modes + insulation optimization"

Centralized heating: The steam pipeline of each double-layer four-mold curing press enters through a high-pressure steam Φ40 main pipe (pressure 1.6 MPa, temperature 201 ℃, providing the four molds with an internal heat source for curing.

The hot plate heating steam Φ25 provides heat source for the four-mold hot plate and mold sleeve; the hot plate and mold sleeve utilize separate steam flow regulating valves, with a total of four sets of regulating valve devices (adjustment accuracy ±0.1 $m^3$/h). Four sets of temperature sensors are employed, and the analog PID algorithm is used to control the temperature control accuracy of ±1.5 ℃ for each mold, with a temperature difference between the four molds of ≤2.0 ℃.

Thermal insulation optimization: Install a 25 mm thick aluminum silicate wool insulation layer (thermal conductivity ≤0.03W/(m·K)) on the outer side of the upper curing press chamber to address the issue of "rapid heat dissipation and temperature difference exceeding 2 ℃" in the double-layer four-mold curing press equipment.

## 1.3 Design for automation and maintenance convenience

### 1.3.1 Full-process automation integration

Equipped with a fully automatic and independent manipulator device

(1) Tire storage manipulator device: With a load capacity of 200 kg and a positioning accuracy of ±1.0 mm, the manipulator tire storage rack can store tire blanks of different specifications (diameter ranging from 510 to 850 mm). Two sets of upper and lower tire storage manipulator racks are arranged on each side. The lower tire storage manipulator rack is fixed, while the upper one is movable up and down. The lower position allows for easy placement of tire blanks, and the upper position facilitates tire blank grasping operations.

(2) Tire loading manipulator device: With a load capacity of 500 kg and a positioning accuracy of ±1.0 mm, the tire loading manipulator can grasp tire blanks of different specifications (bead size: 12″-17″, outer diameter of tire blank: 510~850 mm)

(3) By utilizing visual monitoring, the state of the tire blank during its finalization can be controlled or observed, enabling the identification of deviations in the tire blank's finalization process and prompting timely reminders or indications.

### 1.3.2 Maintenance convenience optimization

(1) Considering the upper-level operation and maintenance, the installation foundation is located approximately below the operation level 0.00 (-1350), facilitating maintenance or operation for both the lower and upper levels.

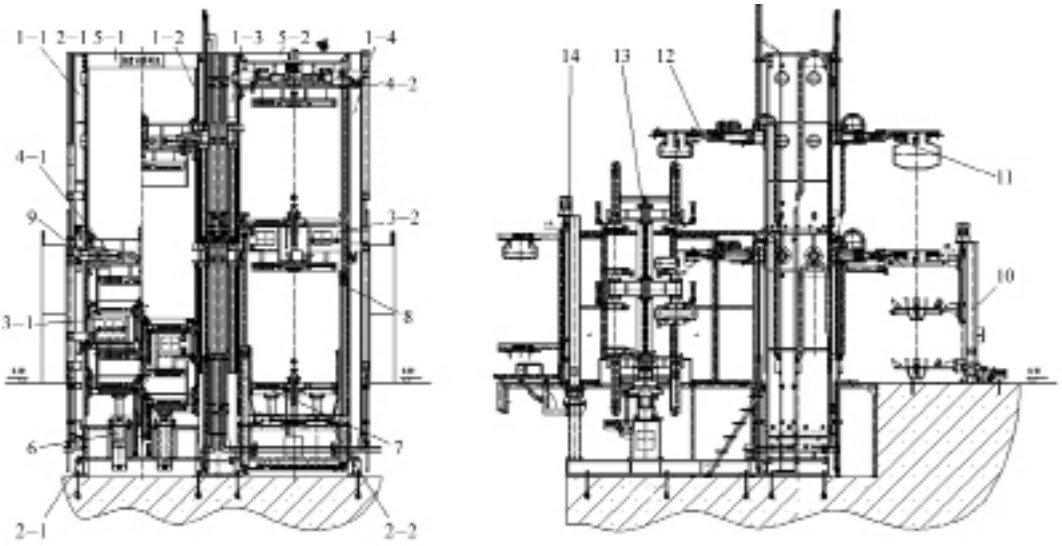
(2) Upper-level maintenance: A reversible maintenance platform (with a load capacity of 300 kg and a reversible angle of 0~90°) is designed, equipped with safety railings and lighting, allowing maintenance personnel to quickly access the upper level space.

(3) A mold change position has been set up, with the upper movable beam (at the position of the upper mold mounting bolts) located approximately above the 0.00 level (+1560 mm), facilitating the replacement or operation of both the lower and upper molds.

(4) The mold clamping and pressurizing hydraulic cylinder device is installed at the lower base for ease of maintenance or operation.

(5) Online detection and diagnosis can be implemented. Key components (such as temperature, pressure, and servo motors) are all equipped with RS485 interfaces, allowing real-time monitoring data to be uploaded to the cloud platform. It supports equipment fault warnings and remote equipment fault diagnosis.

# 2 Improvement of manufacturing process for double-layer four-mold curing press




Illustrative diagram of double-layer four-mold curing press: 1-1, 1-2.1-3, 1-4—frame column; 2-1, 2-2—left and right bases; 3-1, 3-2—left and right middle movable crossbeams; 4-1, 4-2—left and right upper movable crossbeams; 5-1, 5-2—left and right top crossbeams; 6—mold clamping and locking hydraulic cylinder device (4 sets of cylinders on each side); 7—middle mold opening and closing hydraulic cylinder; 8—upper mold opening and closing hydraulic cylinder; 9—left and right mold locking cylindrical pin locking device; 10—left and right tire storage device (upper and lower layers); 11—left and right tire loading manipulator device (upper and lower layers); 12—left and right tire retrieval device (upper and lower layers); 13—left and right rear inflation device (2×4 stations, front and rear rotating type); 14—tire ejection manipulator device (upper and lower layers).

**Figure 1 Double-layer four-mold hydraulic curing press**

### 2.1 Processing of key components of the frame

(1) Left and right columns: The process involves "welding structural components - aging treatment - CNC boring and milling - CNC inspection", ensuring that the parallelism error of the left and right planes is ≤0.015 mm/m;

(2) Upper, middle, and base beams: The process involves "welding structural components - aging treatment - CNC boring and milling - CNC inspection", ensuring that the parallelism error of the upper and lower planes is ≤0.015 mm/m, thereby ensuring consistent installation benchmarks for the double-layer mold.

### 2.2 Modular assembly and precise debugging

#### 2.2.1 Modular assembly process

(1) The equipment is divided into 12 major independent modules (left and right columns, upper movable beam, middle movable beam, lower base, tire storage device, tire loading device, tire unloading device, front and rear rotary rear inflation device, tire ejector device, vulcanization thermal pipeline control, hydraulic control, and electrical control system, etc.), which are pre-assembled on a dedicated tooling platform (with tooling positioning accuracy of ±0.02 mm).

(2) Four modules, including the left and right columns, as well as the upper, middle, and base beams: pre-assemble the columns and beams, ensuring the parallelism and perpendicularity between the columns and beams to be ≤0.02 mm respectively.

(3) Four-mode temperature control module: Pre-installed with steam pipeline, flow valve, and sensor, test the response speed of single-mode temperature control (≤0.1s).

(4) Automated loading and unloading of tire blanks and tire modules: Four sets of (storage, loading, grasping, and retrieval) manipulator devices, vision system, and debugging of positioning accuracy (±0.1 mm).

The assembly is completed using a modular pre-assembly process, which can shorten the cycle by about 30% compared to the traditional bulk assembly cycle, from the original 2 months to about 45 days.

#### 2.2.2 Phased precise debugging

(1) Synchronization debugging: Set up a three-stage test: "no load → half load → full load". The synchronization error of the four-mode opening contract should be ≤0.3 mm under no load, and the synchronization error should be ≤0.5 mm under full load (clamping force of 1,900 kN);

(2) Four-die temperature control debugging: Simulate sulfur vulcanization conditions (temperature 200 ℃, pressure 16 MPa) and run continuously for 48 hours, record the temperature data of the four dies. By fine-tuning the steam flow regulating valve, ensure that the temperature difference of the four-die hot plates is ≤1.5 ℃;

(3) Integrated machine linkage test run: starting from tire storage - upper and lower rings, automatic tire loading by manipulator - shaping - mold closing - pressure vulcanization - normal vulcanization - end of vulcanization - upper and lower rings, automatic tire removal by manipulator - rear inflation - tire removal and transfer to the finished tire conveyor line. The fully automated operation is relatively stable and reliable, with no malfunction for 72 hours of operation.

## 3 Performance verification and industrial application

Taking the design and development of a double-layer four-mold hydraulic curing press as the object, it has been verified in industrial production (curing production of 195/65R15 passenger car tires) for more than one year in tire enterprises. The key performance indicators for inspection and testing are as follows:

### 3.1 Performance

(1) Indoor performance

Experiments were conducted on some representative specifications of semi-steel radial tires with double-layer four-mode vulcanization, and finished product performance tests were carried out for comparison. The results showed that all performance tests of the double-layer four-mode vulcanized tires were superior to the national standard performance requirements.

(2) Uniformity, dynamic balance

We selected specifications from regular mass production for uniformity and dynamic balance testing and comparison verification. It was found that the double-layer four-mold curing press has a minimal impact on uniformity and dynamic balance, which is within a controllable range and meets the requirements. The following table compares the uniformity and dynamic balance data of double-layer four-mold curing tires with traditional single-layer two-mold tires (taking the 195/65R1591V product as an example):

**Table 1 Test results of high speed, durability, strength, and bead unseating resistance**

| Specification | Test method | National standard performance requirements | Double-layer four-mode testing |
|---|---|---|---|
| 195/65R1591V | GB/T4501-2023 | 60 min | 84 min/91 min |
| 195/65R1591V | GB/T4501-2023 | 35.5h | 107.5h |
| 195/65R1591V | GB9743-2015 | 8890N | 9979N |
| 195/65R1591V | GB9743-2015 | 295J | 531J |

**Table 2 Test results of the outer edge**

| Project | Specification | Test method | National standard requirements | | | Test results of dual-layer four-mode tires | | |
|---|---|---|---|---|---|---|---|---|
| | | | Outer diameter | Total width | Wear mark height | Outer diameter | Total width | Wear mark height |
| Outer edge | 195/65R1591V | GB/T521-2023 | 635 mm<br>628-642 mm | 201 mm<br>193-205 mm | No less than 1.6 mm | 634 mm | 204 mm | 1.9 mm |

**Table 3 Impact of double-layer four-mold curing press on uniformity and dynamic balance**

| Category | Serial number | Uniformity testing results | | | | | Dynamic balance test results | | |
|---|---|---|---|---|---|---|---|---|---|
| | | RFV | R1H | LFV | L1H | CON | Static | UPPER | LOWER |
| Single-layer dual-mode | 1 | 7.15 | 5.23 | 4.12 | 3.18 | -3.06 | 358.9 | 15.26 | 18.9 |
| | 2 | 6.73 | 5.16 | 4.23 | 3.16 | -1.35 | 600 | 5.16 | 21.02 |
| | 3 | 6.45 | 4.52 | 3.22 | 2.18 | -1.65 | 455.8 | 10.25 | 16.12 |
| | 4 | 5.16 | 4.23 | 3.12 | 2.16 | -2.03 | 288.9 | 4.61 | 13.78 |
| | mean | 6.11 | 4.64 | 3.52 | 2.5 | -1.68 | 448.23 | 6.67 | 16.97 |
| Double-layer four-mode | 1 | 7.56 | 6.62 | 4.65 | 4.84 | -2.15 | 481.5 | 15.03 | 6.98 |
| | 2 | 8.16 | 6.58 | 4.56 | 4.36 | -3.5 | 699.8 | 19.94 | 12.83 |
| | 3 | 9.12 | 8.16 | 5.16 | 4.82 | -3.26 | 479.05 | 30.12 | 15.16 |
| | 4 | 8.15 | 6.43 | 5.48 | 5.19 | -3.56 | 455.6 | 15.89 | 16.17 |
| | mean | 8.25 | 6.95 | 4.96 | 4.8 | -3.12 | 528.99 | 20.25 | 12.79 |

### 3.2 Capacity and Precision

After nearly six months of continuous production and usage statistics, the average daily production is 450 units (an increase of 180% compared to single-layer dual-mode).

### 3.3 Power consumption and stability

The energy consumption per unit tire vulcanization is 0.8 kW·h, which is 22% lower than that of traditional equipment. The equipment has a continuous operation failure rate of 0.35% per year, which is lower than the design target of 0.4% per year.

### 3.4 Production flexibility

Supports unrestricted replacement of tire specifications ranging from 12 to 17 inches, with a mold change time of 35 minutes per instance, meeting the production enhancement needs of tire companies.

## 4 Conclusion

Through the design, research, development, and manufacturing of a double-layer four-mold tire curing press, this article verifies the development direction of curing equipment towards "multi-mold, automation, and low energy consumption". The core achievements are as follows:

(1) Breakthroughs have been made in the technology of force balance and four-mode synchronous control for a dual-layer structure, resolving the contradiction between high productivity and high precision.

(2) Optimize precision manufacturing and modular assembly processes to enhance equipment stability and maintenance convenience.

(3) Industrial applications have shown that the equipment can meet the needs of large-scale tire production, with significant economic and environmental benefits.

## 5 Future research and development can be deepened in several directions

(1) Innovation in materials and structures: Adopting better structures and materials to increase the overall strength or reduce the weight of the curing press.

(2) Smart Upgrade: Integrate digital twin technology to achieve virtual simulation and fault warning throughout the entire equipment lifecycle (with an accuracy rate of ≥95%).

(3) Green transformation: Adopt electric heating nitrogen direct vulcanization to reduce or eliminate steam vulcanization; improve or enhance the synchronization accuracy of operation (tender error rate ≤0.5 mm).

(4) Further enhance or improve the automation integration with the preceding or subsequent process steps, reduce human intervention, and increase the automation rate of the equipment to over 95%.

